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Thermal Protection System Flight Repair Kit

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MARTIN MARIETTA

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THERMAL PROTECTION SYSTEM FLIGHT REPAIR KIT

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FOREWORD

This final report for the Tile Protective System (TPS) Flight Repair Kit is submitted by Martin Marietta in accordance with Exhibit A, Statement of Work (SOW) and the Data Requirements List (DRL) Line Item No. 2 for Contract NAS9-15969.

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Table

1.0 INTRODUCTION AND SUMMARY

This program defined a thermal protection system (TPS) flight repair kit required for use on a flight of the Space Transportation System (STS-1). Loss of ceramic tiles (TPS) could jeopardize the safety of the crew during the reentry flight phase of the Shuttle orbiter. Therefore, a means of making TPS repairs in orbit must be provided for use, if necessary, by the crew via extravehicular activity (EVA). The manned maneuvering unit (MMU) and a work restraint would be used with the flight repair kit to make the necessary repairs.

Previous NASA activities have led to selection of a cure-in-place ablator using an applicator/mixer unit as a repair technique for full or partial tile damage. For larger area repair, precured ablator sections will be bonded on using the cure-in-place ablator as an adhesive and gap filler. If coating repair is determined to be necessary, an emittance agent will be used in a suitable applicator (being developed by NASA).

Martin Marietta's extensive experience using silicone ablators and man-in-space activities provided us with a good base to perform this program. The objective of this program was to define (1) a cure-in-place ablator, (2) a precured ablator (large-area application), and (3) packaging design (containers, mixing and dispensing). Figure 1-1 presents our two candidate applicator/mixer concepts (self-contained unit and three-part unit) that resulted from this flight repair kit conceptual design activity.

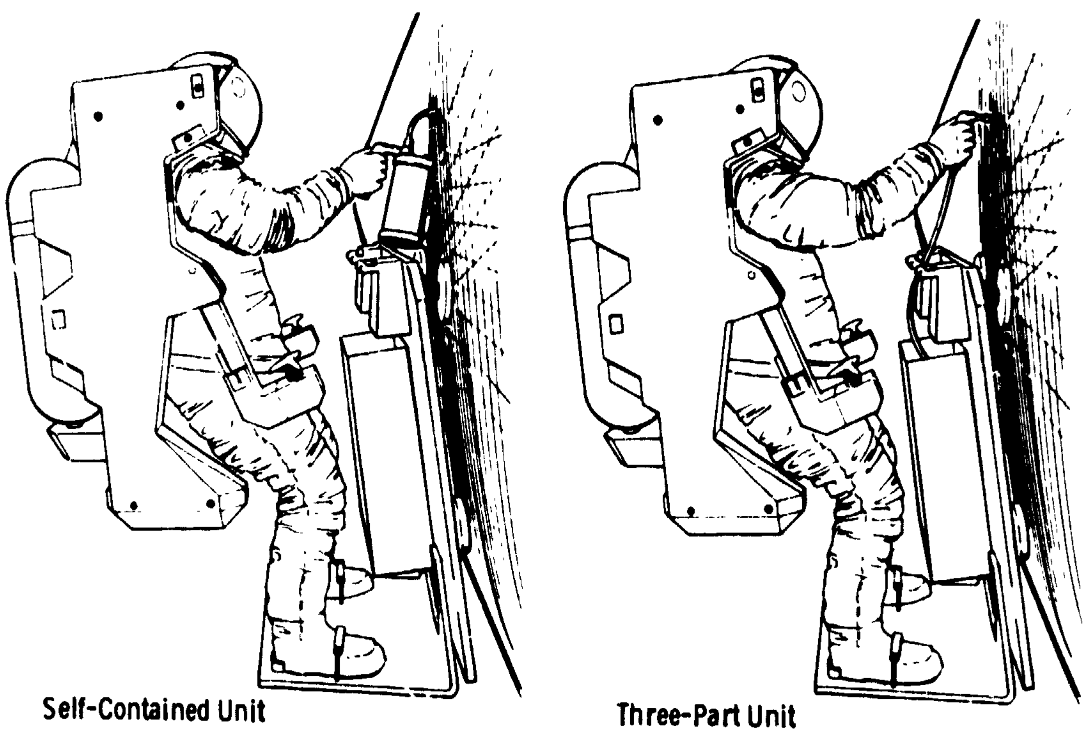


Figure 1-1 Candidate Applicator/Mixer Concepts

The basic program guidelines for the ablator evaluation and selection were:

1) Use available "off-the-shelf" silicone-based material or modification thereof;

2) Satisfy cure-in-space environment, cure time, and temperature range;

3) Must be compatible with RTV 560 (used to bond tile);

4) Require minimal substrate preparation;

5) Have low density;

6) Cure-in-place ablator must be compatible with precured ablator;

7) Must provide satisfactory thermal and structural performance;

8) Must be compatible with cold-soaked conditions.

The basic program guidelines for design of the packaging container and elements (mixing, dispensing and adhesive spreading devices) were (1) satisfy storage capability, (2) satisfy Shuttle-induced environment, and (3) satisfy crew EVA handling interfaces with MMU.

The key design features of our flight repair kit and the associated operational use are:

1) The selected ablator materials have demonstrated superior structural strength, thermal performance in plasma arc testing, and excellent mixing and curing in a vacuum chamber;

2) The two applicator/mixer designs (for cure-in-place material) are straightforward and have been demonstrated in functional mockup tests and by NASA on the KC-135 (zero-g testing);

3) Mixing can be done in the container and was actually done in the functional mockup using both real and simulated catalysts.

Our program plan shown in Figure 1-2 comprised an 11-week technical effort, including a final briefing, a final report, and ablator materials and two applicator/mixer functional mockups delivered to NASA-JSC. The four program tasks with 13 subtasks presented in Figure 1-2 are summarized in the following subsections.

Figure 1-2

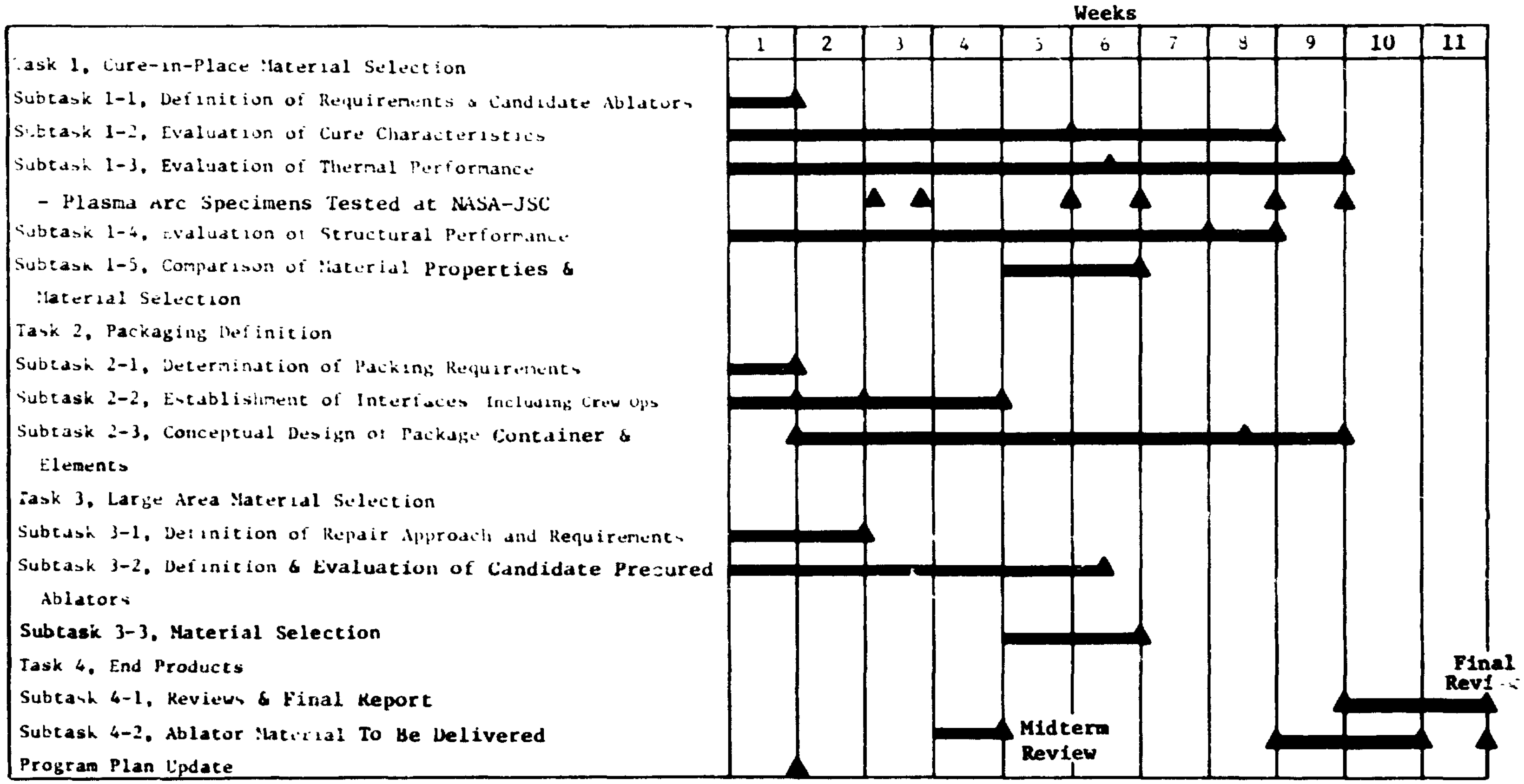


Figure 1-2 Program Milestone Schedule

1.1 TASK 1, CURE-IN-PLACE MATERIAL SELECTION

We defined the requirements and proposed three candidate ablators for evaluation. We conducted an investigation of cure characteristics, mixing, flow and wetting, thermal (plasma arc tests at NASA-JSC), structural performance, and other physical properties to select one cure-in-place ablator material. The five subtasks included:

1) Subtask 1-1, definition of requirements and candidate ablators;

2) Subtask 1-2, evaluation of cure characteristics;

3) Subtask 1-3, evaluation of thermal performance;

4) Subtask 1-4, evaluation of structural performance;

5) Subtask 1-5, comparison of material properties and material selection.

1.2 TASK 2, PACKAGING DEFINITION

We determined package requirements for the cure-in-place and precured ablator TPS repair kits. The interfaces, including crew operation, were then established so conceptual design could be conducted for package containers and various elements. We fabricated and delivered two applicator/mixer functional mock-ups. The subtasks were:

1) Subtask 2-1, determination of packaging requirements;

2) Subtask 2-2, establishment of interfaces, including crew operations;

3) Subtask 2-3, conceptual design of package container and elements.

1.3 TASK 3, LARGE-AREA MATERIAL SELECTION

We defined the repair approach and requirements for the precured ablators. Candidate ablators were then defined and evaluated to select one precured ablator. The three subtasks included:

1) Subtask 3-1, definition of repair approach and requirements;

2) Subtask 3-2, definition and evaluation of candidate precured ablators;

3) Subtask 3-3, material selection.

1.4 TASK 4, END PRODUCTS

We defined the repair approach and requirements for the precured ablators. Candidate ablators were then defined and evaluated to select one precured ablator. The two associated subtasks included:

1) Subtask 4-1, final report;

2) Subtask 4-2, ablator material to be delivered.

The logic flow for the three major technical tasks is shown in Figures 1-3, 1-4 and 1-5.

The key program issues and our approach for solving them are presented in Table 1-1.

Table 1-1 Program Issues and Approach

Issue	Our Approach
1. Cure Characteristics in Space environment for Cure-in-Place ablator	1. Evaluation tests in vacuum for a range of temperatures.
2. Workable Preliminary Designs for Cure-in-Place Ablator Applicator/Mixers	2. Preliminary Designs - Considered detail crew operations - Used state-of-art technology - Applicator/mixer envelope mockups for crew handling evaluation - Fabrication of functional mockup
3. Program Risk	3. Minimized Program Risk by considering total system aspects: - Requirements - Materials - Thermal - Structural Strength - Design & Stress - Electrical - Crew Operations & Safety - Ease of Fabrication - Quality Control

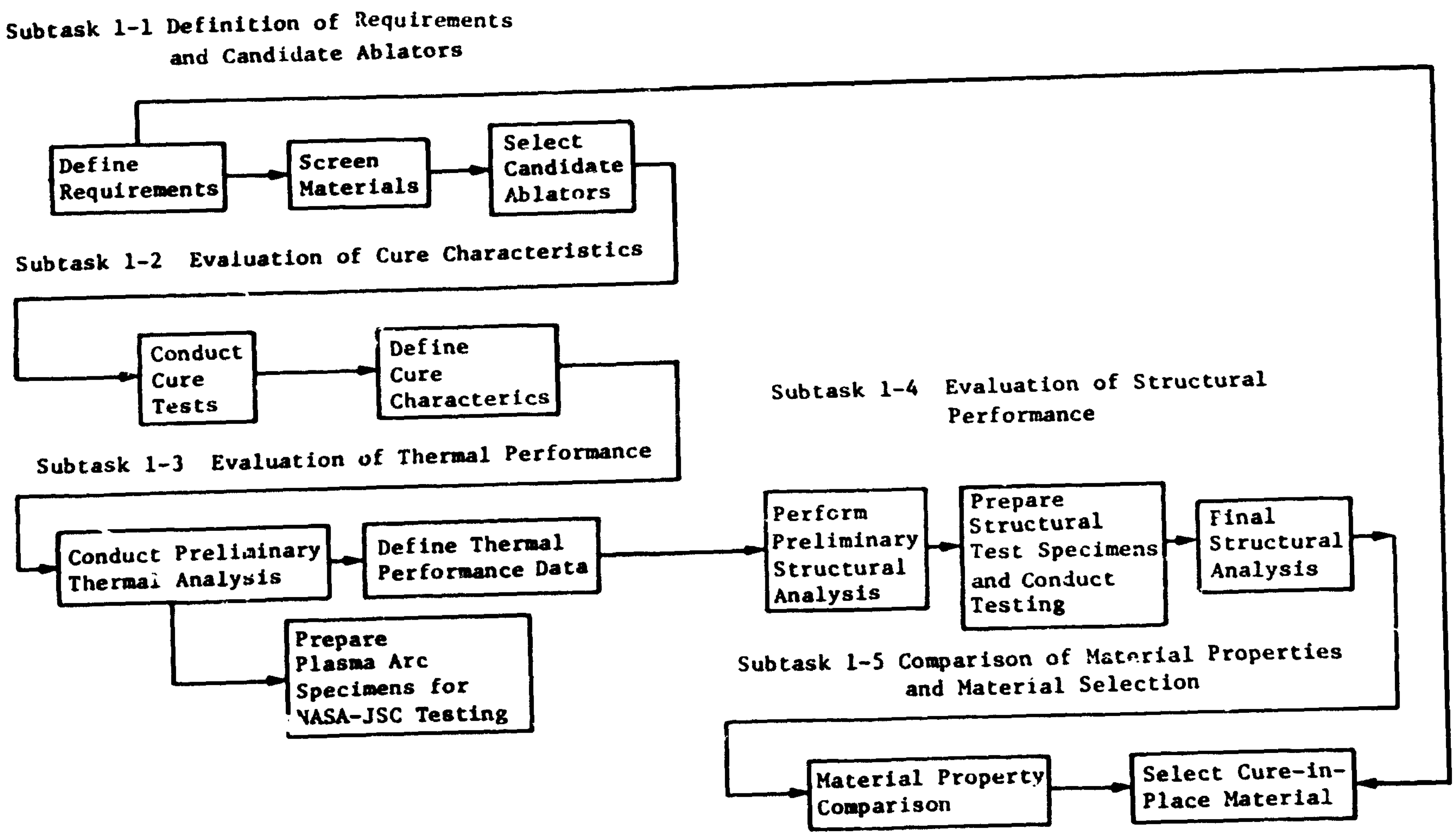


Figure 1-3 Task 1 - Cure-in-Place Material Selection

Figure 1-4

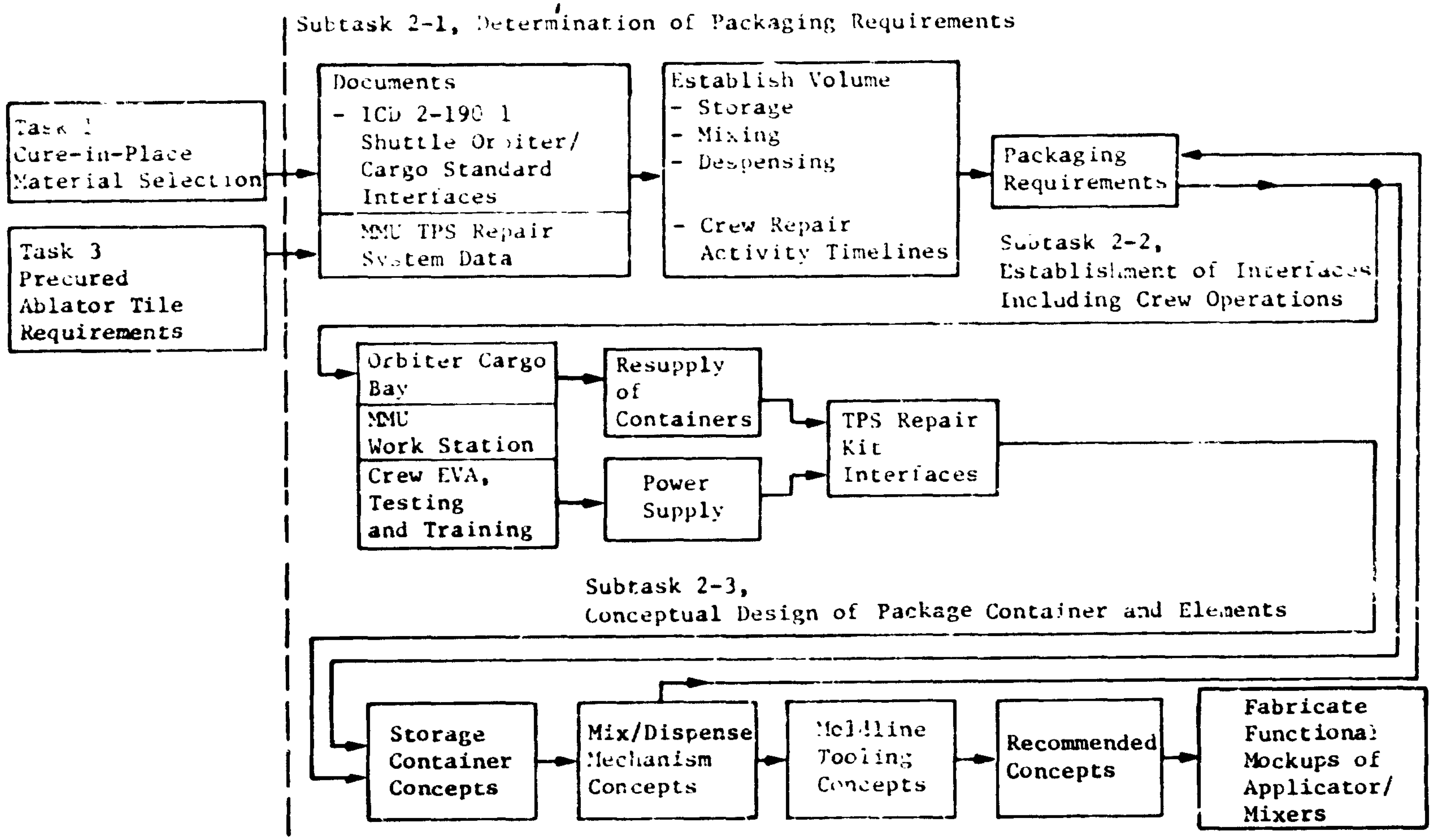


Figure 1-4 Task 2 - Packaging Definition

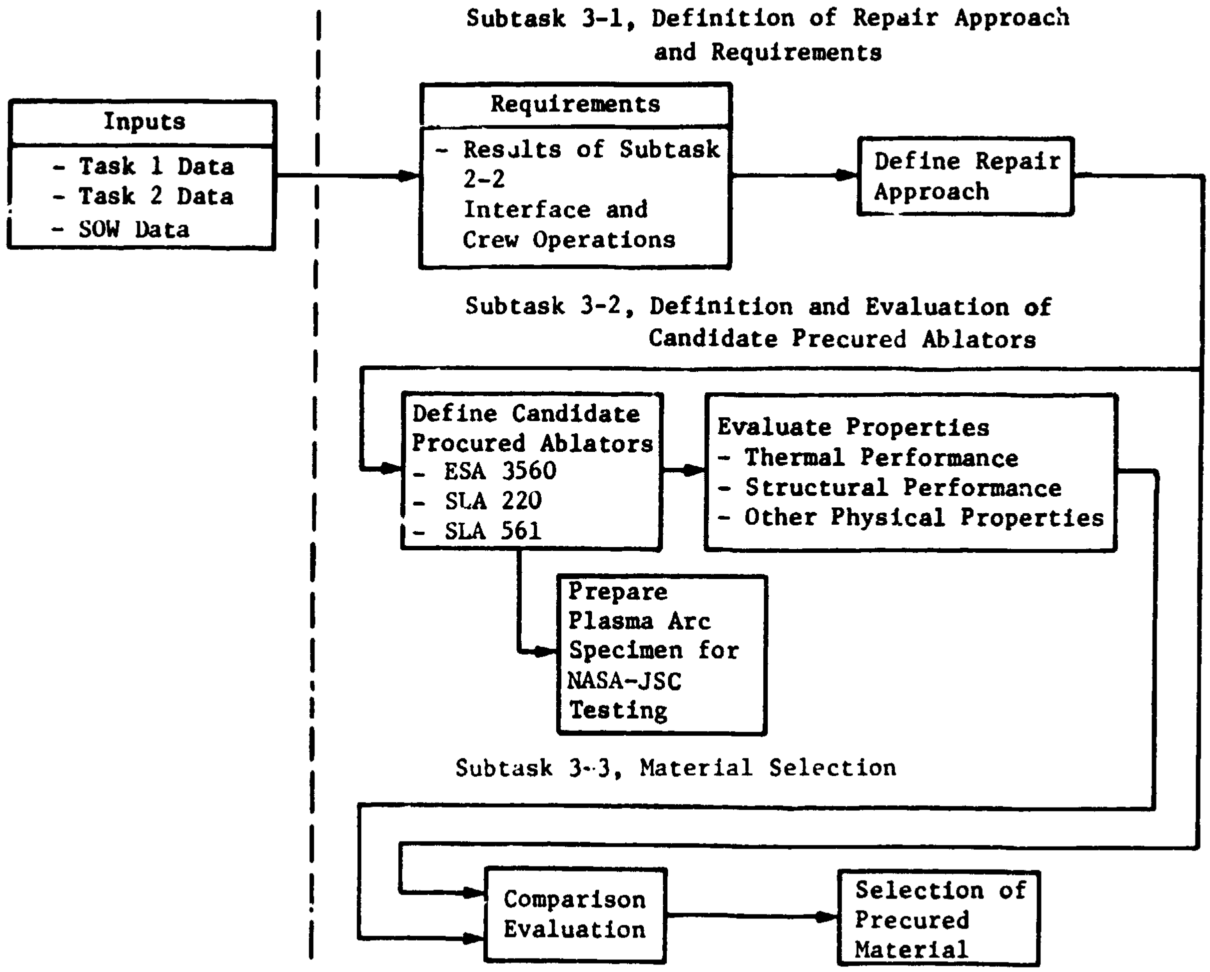


Figure 1-5 Task 3 - Large-Area Material Selection

2.0 REQUIREMENTS

The cure-in-place material must satisfy two functions: (1) it must serve as an acceptable ablator for use in tile cavities, and (2) it must also perform as an acceptable adhesive and gap filler when used in conjunction with precured ablators for large-area repair.

The requirements for selection of the cure-in-place ablator encompassed the following:

1) Use available "off-the-shelf" silicone-based material or modification thereof;

2) Satisfy cure time (perform gel-cure inspection initially in 15-30 minutes, then extend . 1 hour and complete cure in 18 hours);

3) Cure in a space environment with a temperature range of 40 to 125°F;

4) Must be compatible with and capable of wetting and curing while in contact with RTV 560;

5) Have low thermal conductivity (thermal performance);

6) Have a minimum of 40 psi through-the-thickness strength and bond strength (structural performance);

7) Must be compatible with cold-soaked conditions;

8) Have char retention during ablation;

9) Satisfy contamination effects for surface bonding;

10) Satisfy other physical properties such as shelf life, viscosity, hardness, emissivity, etc.

The requirements for the precured ablator consisted of the following:

1) Use available "off-the-shelf" silicone-based material (no development);

2) Must be compatible with cure-in-place ablator;

3) Have low thermal conductivity (thermal performance);

4) Provide a minimum of 40 psi through-the-thickness strength (structural performance);

5) Be compatible with cold-soaked conditions;

6) Have char retention during ablation;

7) Have low density;

8) Satisfy contamination effects for surface bonding;

9) Satisfy other physical properties such as hardness, emissivity, etc.

The requirements for design of the packaging container and elements encompassed the following:

1) Satisfy baseline TPS damage extent and location (establishes volume);

2) Provide the number of package units to satisfy EVA operations;

3) Have stowage area capability (orbiter, inflight tile repair system (ITRS) and MMU packaging constraints);

4) Satisfy tether aspects;

5) Allow EVA crewman handling;

6) Satisfy induced environment of orbiter and MMU;

7) Provide moldline plate (if required);

8) Provide thermal control during mixing (if required);

9) Satisfy material properties of viscosity, density and mixing temperature;

10) Provide a material storage life of six months.

3.0 MATERIAL EVALUATIONS

The materials for the two ablators selected for use in the TPS flight repair kit are well characterized and have demonstrated a reentry performance capability.

The precured ablator, SLA 561, was developed for the Viking project and was thoroughly evaluated for service in that activity. The SLA 561 can totally satisfy the TPS flight repair requirements and was selected. The process used to prepare Viking material was altered to delete the requirement for reinforcement and thermal sterilization of the constituents, thereby simplifying fabrication of the precured material.

The cure-in-place ablator, MA 25S, is a mature formulation that has been successfully used in prior applications. To provide the ability to apply this ablator in space, the established formulation was modified. This modification (Type III) has been established and shown in this contract work to be completely satisfactory for the intended application.

Martin Marietta has had a successful history of developing numerous thermal protection systems for various flight programs. Our candidate selection in this contract was based on this level of background knowledge. Final selection was made as a result of evaluation of property and performance data as well as our knowledge of the anticipated behavior of the proposed system modifications.

During previous flight system programs, Martin Marietta has developed several silicone ablators/insulators ranging in density from 14 to 55 lb/ft^3. Typical examples of these materials are ESA 3560, ESA 5500, MA 25S, SLA 220 and SLA 561. These ablators have been qualified for use in the PRIME, X-15 PAET, Titan IIIC payload fairing, Viking, CF6 fan reverser, and Space Shuttle external tank (ET) programs.

Repair materials that cure at room temperature without supplemental (vacuum bag) pressure have been developed for these ablator systems. Three repair compositions (SLA 561 handpack, JS 220, and MA 25S Type II), all flight-qualified and documented by validated material specifications and processes, were selected as cure-in-place candidates that could be modified for the flight repair kit application.

Handpack SLA 561 is a closeout and repair material for SLA 561 used on the external tank. It has been qualified for use on ET by wind tunnel tests in AEDC Hypersonic Tunnel C, by installation on Minitanks No. 9 and 11 and on a 10-foot diameter test tank, and by evaluation in an Instrument Island simulation test. Within past months, plasma arc testing of handpack SLA 561 has been conducted at NASA-LRC. The gel time of the RTV 652 resin used in SLA 561 handpack is 7 to 12 minutes. The 45-minute working life is achieved by adding heptane, which retards resin cure.

JS 220 was developed as a repair material for the SLA 220 (RF-transparent) heat shield used on the radio altimeter of the Viking Mars lander. JS 220 has also been supplied to Ball Brothers Research Corporation (PO 31025) for use as a repair material of the SLA 220 heat shield for a Minuteman flight test antenna. The JS 220 working life of 2 hours is achieved by using a blend of RTV 652 (room temperature setting) and RTV 655 (elevated temperature setting) silicone resins.

MA 25S Type II is a repair material for the MA 25S sprayable silicone insulation system for the CF6 fan reverser. Its composition is identical to that of the MA 25S spray ablator after solvent evaporation. MA 25S is also being used on ET in certain shock interference heating regions. It has been qualified for use on ET by wind tunnel tests. Similar to SLA 561 handpack, the working life and viscosity of MA 25S Type II is controlled by heptane addition.

3.1 CURE-IN-PLACE ABLATORS

The evaluation of the cure-in-place ablator consisted of a three-step process in which the environmental conditions associated with the ablator were altered as shown in Table 3.1-1. The three conditions permitted preparation under (1) atmospheric pressure in the temperature range of 40 to 125°F, (2) vacuum in the temperature range of 40 to 125°F, and (3) <u>in situ</u> vacuum at room temperature and at 100°F.

Table 3.1-1
Cure Characteristics Evaluation - Three Steps

1. Atmospheric Conditions (40 - 125°F)
   - a) Mixing (viscosity)
   - b) Compatibility
   - c) Gel Times
   - d) 18-hour Cure
   - e) Density
   - f) Bond Tension
   - g) Shore A Hardness
   - Preparation of Plasma Arc Specimens
2. Vacuum Conditions (40 - 125°F)
   - a) Mixing Basic Materials in Atmosphere
   - b) Degas Resin/Fillers in Vacuum
   - c) Mixing Resin/Fillers with Catalyst Using Vacuum Mixer
   - d) Gel Times & 18-hour Cure (Bell Jars, Small Oven & Walk-In Refrigerator)
   - e) Compatibility f) Density g) Bond Tension
   - h) Shore A Hardness
3. In Situ Vacuum Chamber Conditions (Room temperature)
   - a) Mixing and Making of All Aspects of the Materials
   - b) Gel Times c) 18-hour Cure d) Compatibility
   - f) Density g) Bond Tension h) Shore A Hardness

The basic approach used was to modify the candidate compositions to remove the volatile heptane and reduce the percentage of fillers for viscosity control.

Under the atmospheric conditions study, the first evaluation consisted of determining gel time as a function of temperature for the RTV 652/655 resin blend. As shown in Table 3.1-2, the gel time was temperature-sensitive.

Table 3.1-2
Cure Characteristics Evaluation - Atmospheric Conditions - Step 1

Determined Gel

Times (40 - 125°F) RTV 652/655 Resin Blend
Results:
- 40°F - 3 hr 15 minutes
- RT - 15 minutes
- 125°F - 2 minutes

→ **Determined**

RTV 652/655 Resins Not Compatible with Curing on RTV 560

→ **Evaluated:**

1) Putting Primer Materials Over RTV 560, Then Applying Ablator
2) Substitution of RTV 511 Resin

Selected Substitution of RTV 511 Resin

- Compatible with RTV 560
- Good Bond Tension Strength
- Minimizes Crew Operations on Orbit

→ Addition of RTV 910 Diluent and reduction of filler materials to improve viscosity

→ Conducted material property tests and prepared plasma arc specimens

It was determined that the RTV 652/655 resin combination was not compatible with curing on RTV 560. Two options were evaluated--priming the RTV 560 prior to ablator application, and substitution with a compatible resin. Resin substitution was selected because it eliminated the necessity for an additional onorbit operation (priming). The selected substitute, RTV 511, is compatible with RTV 560 and exhibits good bond tension strength. RTV 910 was added to the RTV 511 resin as a diluent to improve viscosity. The resulting materials are identified as the Type III modifications; compositions are shown in Table 3.1-3.

Table 3.1-3
Definition of Modified Cure-in-Place Materials

Materials	% Resin (RTV 511)	% Diluent (RTV 910)	% Fillers
JS 220 Type III (1.0% catalyst)*	73.3	7.3	19.4 (Eccospheres SI)
MA 25 S Type III (1.25% catalyst)*	73.3	7.3	19.4 (Eccospheres SI) (Silica Fibers) (Fe_2O_3) (Cab-O-Sil)
SLA 561 Type III (.8% catalyst)*	76.3	7.6	16.1 (Eccospheres SI) (Phenolic Microballoons) (Cork) (Carbon black) (Silica Fibers)

* % of resin.

The change of base resin resulted in a most interesting phenomenon with respect to the effect of temperature on gel time. As shown in Table 3.1-4, gel time was essentially uniform over the temperature range from 0 to 125°F.

Table 3.1-4
Ablator Gel Time Evaluation - Minutes and Seconds - Step 1

Atmospheric Conditions

Materials	Temperature			
	0°F	40°F	Room	125°F
JS220 Type III	17'0"	16'10" 19'0" (1)	15'30"	[illegible] (2)
MA 25 S Type III		15'40"	14'50"	14'0"
SLA 561 Type III		16'0"	15'45"	14'35"

Basic Approach

1. Materials mixed at room temperature & then put on substrate.
2. 0.125-in. aluminum plate substrate with 6x6x1-in. (Depth) wood frame (covered with mylar).
3. Aluminum substrate/frames at temperatures shown above for 2 hours.

Note: (1) Material components, mixing and testing at 40°F (3)
(2) Material components, mixing and testing at 125°F (3)
(3) Thermometer in material indicated no increase in temperature

As anticipated, reduction of the filler content resulted in an increase in both density and hardness. As shown by Table 3.1-5, the bond tension strength, 100 psi, was significantly greater than the 40-psi minimum requirements.

Table 3.1-5
Properties of Cure-in-Place Material Formulated Under Atmospheric Conditions

Formulation	Density, lb/ft^3	Shore A Hardness, %	Bond Tension, psi*
JS 220, Type III	40.7	50	100
MA 25S, Type III	43.7	50	100
SLA 561, Type III	42.5	50	100
JS 220	30.7	30	--
MA 25S, Type II	34.3	30	--
SLA 561, Handpack	36.6	30	--

*18-hour cure at 40°F; tested at 40°F; all specimens failed at bondline of aluminum plug to ablator.

The viscosity measurements were taken at room temperature for the Type III materials as shown in Table 3.1-6.

All candidates exhibited a viscosity significantly below the baseline limit condition of 7600 poises, which is the viscosity of RTV 577. Viscosity for MA 25S Type III mixed in vacuum and exposed in situ for 72 hours (Step 3) was measured in air as a function of temperature. The data showed that the vacuum processing increased viscosity. However, the level at room temperature was below the RTV 577 baseline limit condition of 7600 poises. The data are shown in Table 3.1-7.

Table 3.1-6
Viscosity Measurements -
Atmospheric Conditions

		POISES
MA 25S Type III	-	3000
JS 220 Type III	-	2200 - 2400
SLA 561 Type III	-	3400 - 3800
RTV 577	-	7600

MEASUREMENT APPROACH

1. Brookfield test with No. 7 spindle at 2 rpm
2. Room temperature.

Table 3.1-7
Viscosity Measurements

MA 25S Type III - Mixed in Vacuum and Exposed In Situ Vacuum Chamber for 72 Hours

Temperature, °F	Viscosity, Poises
40	8480
74	6080
125	4480

Plasma arc testing was performed at NASA-JSC on specimens of each composition as discussed in Section 3.3. The results showed that the Type III modifications all exhibited improved performance over their respective baselines as evidenced by reduced char depth and weight loss. Although the SLA 561 demonstrated slightly superior performance in terms of temperature response, the difference is insignificant.

Large specimens of MA 25S (6x6x2 in.) were prepared and tested as discussed in Section 3.3. Results confirmed the improved char resistance and reduced weight previously demonstrated.

It was concluded at this point in the evaluation that all Type III candidates were thermally satisfactory for the proposed application and that other factors should govern selection. In fact the thermal performance well exceeded the requirements. The RTV 511 resin clearly demonstrated improved thermal performance, as evidenced by less char, and minimized char layer swelling. A decision was made to eliminate the JS 220 from further evaluation at this point because it might demonstrate a lower performance caused by a lesser ability to retain the char layer because of the absence of silica fibers in the formulation.

As the first step in the vacuum condition evaluation (step 2), the gel time test was repeated using a bell jar, vacuum oven and walk-in refrigerator. The data confirmed the previous finding that the gel time is essentially independent of temperature as shown in Table 3.1-8.

Table 3.1-8
Ablator Gel Time Evaluation - Minutes and Seconds - Step 2

Vacuum Conditions (Vacuum Mixer, Bell Jar, Vacuum Oven & Walk-in-Refrigerator)

Material	Temperature		
	40°F	Room	125°F
MA 25S Type III 2.1% Catalyst*	16'0"	15' 40"	15' 30"
SLA 561 Type III 1.2% Catalyst*	16'0"	15' 40"	15' 10"

Basic Approach

1. Basic material mixed at room temperature in atmosphere.
2. Basic materials (resin / fillers) degassed in vacuum.
3. Resin / fillers mixed with catalyst in vacuum mixer, put on substrate and placed in bell jars & small oven.
4. 0.125-in. aluminum plate substrate with 3x3x1-in. (depth) wood frame (covered with mylar).
5. Aluminum substrate / frames at temperatures shown above for 2 hours.

*% of resin.

Mixing the cure-in-place ablator under vacuum conditions resulted in properties similar to those obtained under atmospheric conditions except for the reduction in bond tension due to some voids. The data are summarized in Tables 3.1-9 and 3.1-10.

In situ vacuum chamber processing (evaluation plan shown in Table 3.1-11) conducted at room temperature and 100°F confirmed the excellent performance of the MA 25S and SLA 561. Although initial processing produced large voids, adequate degassing of the constituent materials minimized void formation to essentially no voids. Density, hardness, and bond tension data for materials containing medium-sized voids (identified as series 1) are summarized in Table 3.1-12.

The techniques for in situ vacuum chamber cure-in-place ablator processing are depicted in Figure 3.1-1. View A shows one of the two Martin Marietta in situ vacuum chambers. Operation of the remote manipulators is shown in View B. View C shows mixing of a small batch of material using the manipulator to hold the container. Pouring of the cure-in-place material is shown in View D.

Table 3.1-9 Cure-in-Place Material Properties - Step 2

Vacuum Conditions (Vacuum Mixer, Bell Jar, vacuum oven, & walk-in-refrigerator)

Materials	Cure & Test Temperature	Density, lb/ft^3	Shore A Hardness	Bond Tension, psi
MA 25S Type III Cured on RTV 560/Aluminum	40°F	41.8	40-45	58
	R.T.	42.2	40-45	42
	125°F	35.6	40-45	45
MA 25 S Type III Cured on RTV 560/SIP/Aluminum	R.T.	39.8	40-45	42
MA 25S Type III Cured Between RTV 560/SIP/Aluminum and Precured SLA 561	R.T.	N/A	40-45	65

Table 3.1-10 Cure-in-Place Material Properties - Step 2

Vacuum Condition (Vacuum Mixer, Bell Jar, Vacuum Oven & Walk-in-Refrigerator)

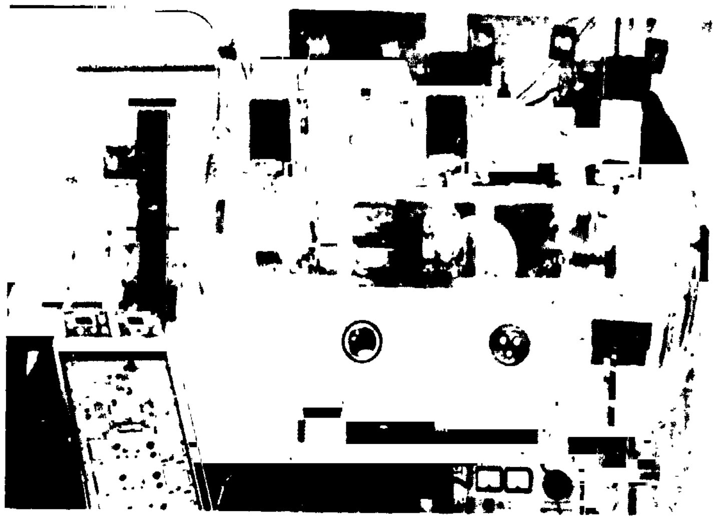
Materials	Cure & Test Temperature, °F	Density, lb/ft^3	Shore A Hardness	Bond Tension, psi
SLA 561 Type III Cured on 560/SIP/Aluminum	40 R.T 125	36.0 34.0 35.0	45 - 50 45 - 50 45 - 50	41 68 63
SLA 561 Type III Cured Between RTV 560/SIP/Aluminum and Precured SLA 561	R.T.	N/A	40	60

Table 3.1-11 Cure Characteristics Evaluation - Step 3

In Situ Vacuum Chamber - Room Temperature and 100°F 1. Establish % catalyst required for 15-minute, 45-minute, and 1-hour gel - MA 25S Type III - SLA 561 Type III 2. Mix and dispense the two materials in vacuum to prepare 15 (3x3x1-in.) ablator test specimens. Test results (density, bond tension, Shore A hardness) used with other data to select one cure-in-place ablator. 3. After selection of the cure-in-place ablator, 9 additional (3x3x1-in.) specimens were fabricated for final material fabrication.

Table 3.1-12
Properties of Cure-in-Place Material Formulated Under In Situ Vacuum Conditions at 70°F (Series 1)

Material	Density, lb/ft^3	Shore A Hardness	Bond Tension, psi
MA 25S Cured on RTV 560/Aluminum	39.8-43.7 (41.9 avg)	40-45	76-118 (101 avg)
MA 25S Cured on RTV 560/SIP*/Aluminum	37.9-42.2 (40.0 avg)	40-45	84-88 (86 avg)
MA 25S Cured Between RTV 560/SIP*/ Aluminum and Precured SLA 561	--	45-50	82-99 (91 avg)
SLA 561 Cured on RTV 560/Aluminum	36.6	40-45	65-70 (67.5 avg)
SLA 561 Cured on RTV 560/SIP*/Aluminum	39.1	40-45	86
SLA 561 Cured Between RTV 560/SIP*/ Aluminum and SLA 561 Precured Material	--	--	60-96 (77 avg)
*Simulated SIP; strength greatly exceeded that of SIP used for orbiter TPS.			



View A

View B

View C

View D

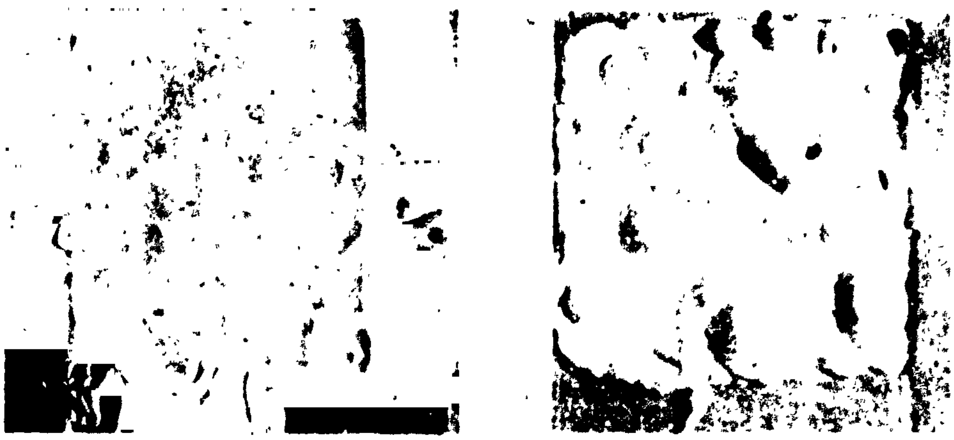
Figure 3.1-1 Techniques for Vacuum Chamber Processing

As a result of the three-step evaluation, we concluded that the cure-in-place ablators satisfy all performance requirements and could be processed under space vacuum conditions. Although the performance characteristics of MA 25S and SLA 561 were similar, the lower viscosity of the former and anticipated better flow characteristics for mixing and dispensing became governing factors in selection of MA 25S Type III as the proposed cure-in-place material (approved by NASA-JSC).

After selection of the MA 25S Type III material, a second series of specimens was tested. Further efforts to reduce void content by additional degassing showed an increase in density. The increase is attributed to void reduction. Data are summarized in Table 3.1-13. Figure 3.1-2 compares the MA 25S material processed by vacuum mixing and degassing in the vacuum chamber for 72 hours or more.

Table 3.1-13
Properties of Cure-in-Place Material Formulated Under In Situ Conditions (Series 2)

Material	Curve and Test Temperature °F	Density lb/ft^3	Shore A Hardness	Bond Tension, psi
MA 25S Cured on RSI Residue/SIP	70 100 (Cure) 350 (Test)	48-50.5 48-50	50 50	15-20* 15-20*
MA 25S Cured on RTV 560/ Aluminum	100 (Cure) 350 (Test)	48.3-50.2	50-60	76-90 (82.5 avg)
*Failed in RSI.				



(a) VM-2 Speciment with Essentially No Voids

(b) VM-3 Specimen with Many Voids

Figure 3.1-2 Comparison of MA 25S Materials

A final evaluation of the effect of temperature on gel time for the MA 25S that had been vacuum-mixed and degassed in the vacuum chamber for 94 hours confirmed the insensitivity of gel time to temperature. The data are shown in Table 3.1-14.

Table 3.1-14
Effect of Temperature on Gel Time

MA 25S Type III - Vacuum-Mixed and Degassed In Situ Vacuum Chamber for 94 Hours

Temperature, °F	Gel Time, Minutes
0	55
40	58
70	68
125	65

3.2 PRECURED ABLATORS

The SLA 561 ablator successfully used on the Viking was the baseline material candidate for the proposed application. Two alternatives, SLA 220 and ESA 3560, were identified as backup materials. The properties of the three ablators are given in Table 3.2-1.

Table 3.2-1 Candidate Precured Ablators

Property	Baseline Material ↓ SLA 561 (Viking)	SLA 220 (Viking) (X-24C)	ESA-3560 (PRIME)
Density, lb/ft^3	14 ± 1	14.5 ± 1	30 ± 2
Tensile Strength, psi	60	85	120
Shore A Hardness	30	30	70-75

The SLA 561 used for Viking contained honeycomb core reinforcement and the constituents were heat-sterilized to eliminate Mars contamination. To confirm that elimination of the reinforcement and sterilization did not alter behavior, two separate billets of precured material were prepared. The properties, tabulated in Table 3.2-2, agreed with anticipated behavior.

Plasma arc testing of one sample of this material (as discussed in Section 3.3) showed performance in agreement with prior work.

Table 3.2-2
Recent Effort on Baseline Precured SLA 561

Fabricated One Plasma Arc Specimen*

Material Properties *, **

Density, lb/ft^3	Tension, psi	Shore A Hardness
12.6	91	50-55

* Fillers not heat-treated as required during Viking project to eliminate contamination on Mars.
** Two separate cured billets.

The SLA 561 was selected as the material composition for the precured ablator application.

3.3 ABLATOR PLASMA ARC TESTS

Twelve ablator specimens were exposed to plasma arc testing during this effort. All tests were performed in either the JSC 5-megawatt facility or their 10-megawatt channel facility. The different tests are summarized in Table 3.3-1. The first nine runs were screening tests made on stagnation models in the 5-megawatt plasma arc. Three tests were run on specimens mounted in the wall of the 10-megawatt channel facility. Two of these tests were made with 6x6x2-inch blocks of ablator and one utilized a 3-inch diameter ablator specimen cured in a 6x6x2-inch HRSI tile. In each case, the 6x6-inch blocks were surrounded by simulated HRSI blocks and tile gaps. The blocks were aligned 45o with respect to the flow. A sketch of the three different test specimen configurations is given in Figure 3.3-1. Pretest photographs of representative stagnation and wedge models are given in Figures 3.3-2 and 3.3-3.

Table 3.3-1 Summary of Plasma Arc Tests Conducted

Type of Test Specimen	Test Condition	Test No.	Ablator Material	Mixing and Cure Environment
Stagnation Model - 2-in.-Diameter Specimen Cured in 3.785-in. HRSI Annular Shroud 2-in. Deep	T_s* = 2600°F	1	SLA 561 Type III	Atmospheric
		2	SLA 561 Handpack	
		3	JS 220 Type III	
		4	JS 220	
		5	MA 25S Type III	
		6	MA 25S Type II	
		7	MA 25S Type III	
		8	JS 220 Type III	
		9	Precured SLA 561	
Wedge Model - 6x6x2-in. Material Specimen	$\dot{q}$ = 36**	10	MA 25S Type III	Atmospheric
	$\dot{q}$ = 20**	11	MA 25S Type III	
Wedge Model - 3-in. Diameter men Specimen in 6x6x2-in. HRSI Tile	$\dot{q}$ = 36**	12	MA 25S Type III	Vacuum

* Surface temperature of Apollo ablator.
** Heating rate on specimen, Btu/ft^2-s.

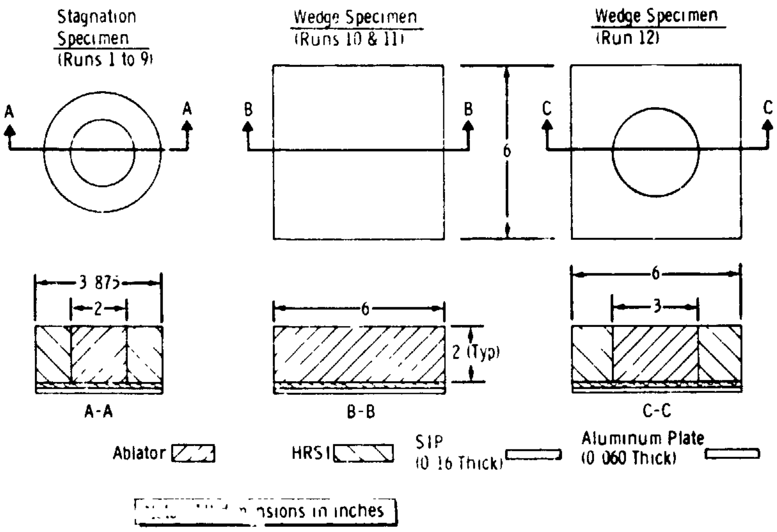


Figure 3.3-1
Plasma Arc Test Specimen Configurations

SLA 561

MA 25S JS 220

- Test Point Selected to Give 2600°F on Surface of Apollo Ablator Enthalpy $\approx$6200 Btu/lb, $\dot{q}$ = 44 Btu/ft^2-s
- Test Consisted of 10 minutes at These Conditions

Figure 3.3-2
Typical Plasma Arc Specimens Prior to Test

Figure 3.3-3
Wedge Plasma Arc Specimen (MA 25S Type III)
Prior to Test

In all model configurations the ablator specimens were bonded to a 0.16-inch thick strain isolator pad that was bonded to an 0.060-inch aluminum backing plate. Thermocouples were installed in all ablator specimens at nominal depths of 1/4, 1/2 and 1 inch from the surface. The first eight screening specimens had thermocouples inadvertantly installed as shown in Figure 3.3-4(a). This type of installation (hereinafter referred to as type a) was judged to be subject to significant conduction errors. Therefore JSC personnel modified the installation to the type shown in Figure 3.3-4(b) for specimens used in tests 1, 5 and 8. The latter type of installation (referred to as type b) minimizes conduction losses by placing the thermocouple wire along an isotherm in the material. Ablator samples for tests 9 through 12 were also instrumented as shown in Figure 3.3-4(b). Since the material specimens for tests 2 through 4 and 6 and 7 had the type a thermocouple installation, the depth temperatures from these tests were considered to have significant measurement errors and were not used.

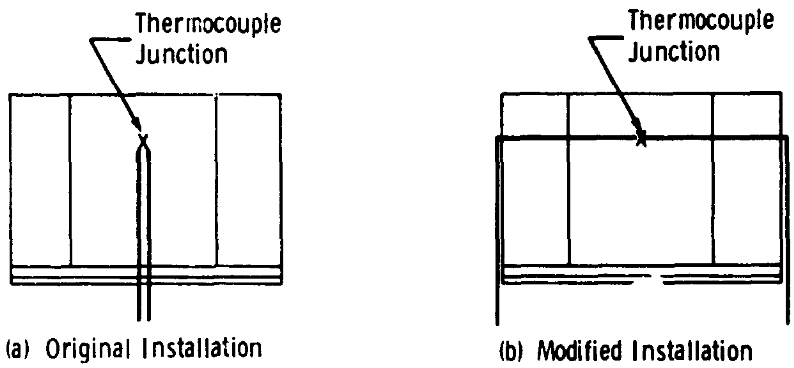


Figure 3.3-4 Ablator Thermocouple Installation

All specimens were x-rayed to verify thermocouple depth. The thermocouples in all the installations were at the desired 1/4, 1/2 and 1-inch positions.

The screening tests (1 through 9) of the candidate ablators were made at a test condition that produced a 2600°F temperature on the surface of the Apollo ablator. Wedge specimens 10 and 12 were exposed to a heating rate of 36 Btu/ft^2-s and test 11 was run at a heating rate of 20 Btu/ft^2-s. All test specimens were exposed to the test environment for a period of 10 minutes. Additional plasma arc parameters for these tests are tabulated.

Test	Heating Rate, Btu/ft^2-s	Stagnation Enthalpy, Btu/lb	Pitot Pressure, psf	Shear Stress, psf
1 through 9	44	6200	27	--
10	36	6800	42	1.79
11	20	4500	35	1.29
12	36	8800	70	2.13

Results from the various plasma arc tests consisted of a comparison of candidate ablator char characteristics and their indepth thermocouple response. Figures 3.3-5 through 3.3-9 show char photographs of most of the various test specimens. Figures 3.3-5 through 3.3-7 compare the char differences due to changing from a 652 resin to a 511 resin. The 511 resin reduces the char layer thickness and swelling for all the candidate ablators. The char associated with the 511 ablators is relatively dense and appears to possess good strength characteristics. Although cracks were observed in the surface of the char, these were thought to have occurred during the cooldown following test exposure.

Tables 3.3-2 and 3.3-3 summarize the plasma arc results for the stagnation and wedge specimens. Table 3.3-2 shows there is not a significant difference in the aluminum temperature response for any of the candidate ablators. Conversely, a comparison of the cure environment effect on the wedge samples (Table 3.3-3) shows a much higher aluminum temperature rise for the vacuum cure, although the strain isolator (SIP) rise is not as great. The fact that the aluminum rise is greater than the SIP rise indicates the aluminum was responding to a heat path other than through the ablator. This is also indicated by Figure 3.3-10, which compares the transient temperature history of thermocouples located 1 inch from the surface of the two MA 25S specimens. It can be seen that the vacuum cure temperature is lower at the 1-inch plane, which also suggests that differences in SIP temperatures may have been caused by the aluminum plate.

Table 3.3-2
Plasma Arc Test Results - MA 25S Stagnation Models

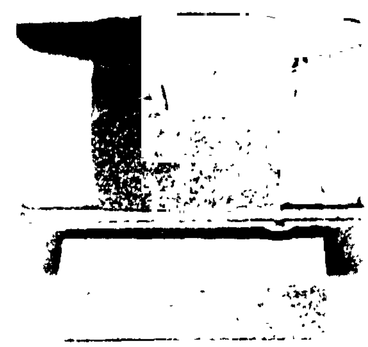
Material	Resin	Char Depth, in.	Weight Loss, %	Max SIP Δ Temperature, °F	Max Aluminum Δ Temperature °F
SLA 561 Precured	655	1.00	21.6	17	13
SLA 561 Type III	511	0.42	8.5	4	8.6
SLA 561 Handpack	652	0.57	11	7.5	8.8
JS 220 Type III	511	0.50	8.4	11.3	9.0
JS 220	652	1.02	13.2	9.6	7.1
MA 25S Type III, No. 1	511	0.48	7.4	15.7	11.6
MA 25S Type III, No. 2	511	0.50	7.2	12.3	8.7
MA 25S Type II	652	0.94	8.2	11.4	11.6

Table 3.3-3
Plasma Arc Test Results (Atmospheric-Prepared Material) - MA 25S Wedge Models

Test No.	Cure Environment	Average Char Depth, in.	Weight Loss, %	Max SIP Δ T, °F	Max Aluminum Δ T, °F
10	Atmospheric	0.53	9.9	8	4
11	Atmospheric	0.45	8.4	3	--
12	Vacuum	0.50	8.1	14	38

SLA 561 Type III (RTV 511 Resin)

Front View



Cross Section

SLA 561 Handpack (RTV 652 Resin)

Front View

Cross Section

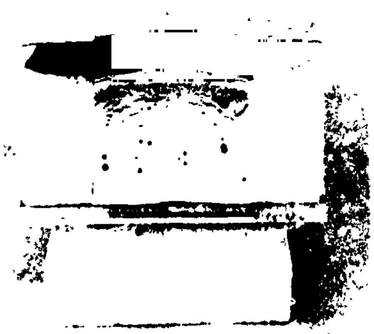
Figure 3.3-5 Plasma Arc Specimens After Test

MA 25S Type III

Front View

Cross Section

Front View



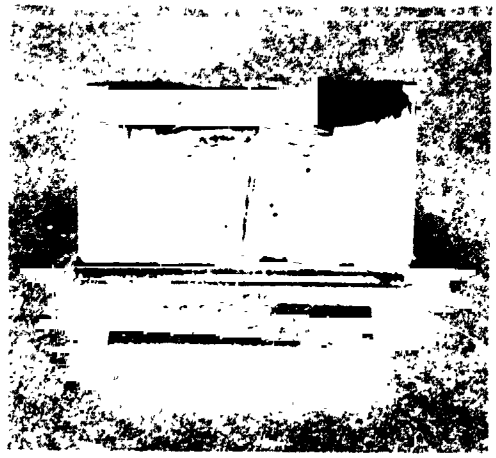
Cross Section

Figure 3.3-6 Plasma Arc Specimens After Test

JS 220 Type III

No. 1

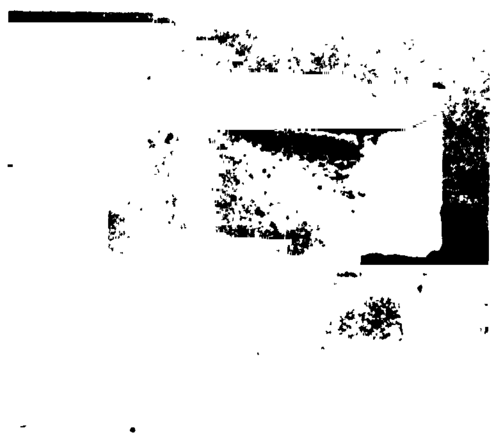
Front View



Cross Section

No. 2

Front View

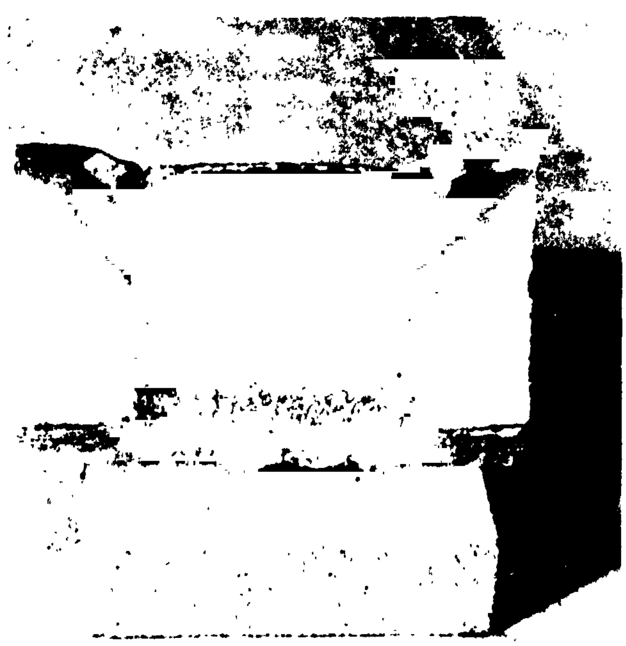


Cross Section

* Results affected by multiple arc shutdowns and restarts.

Figure 3.3-7 Plasma Arc Specimens After Test

Top View



Cross Section

Figure 3.3-8 Precured Ablator (SLA 561) After Test

Figure 3.3-9

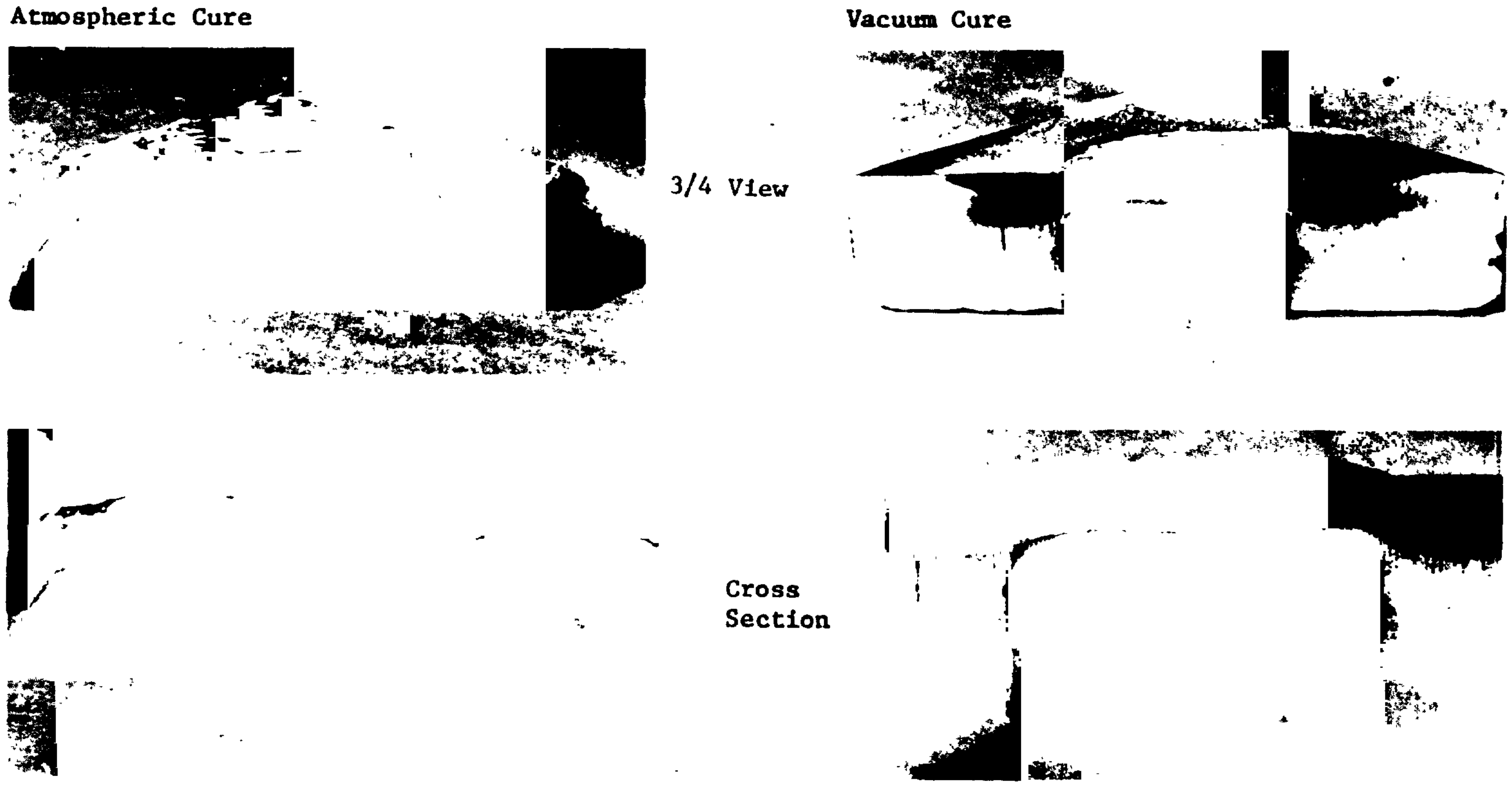


Figure 3.3-9 Comparison of MA 25S Wedge Test Specimens

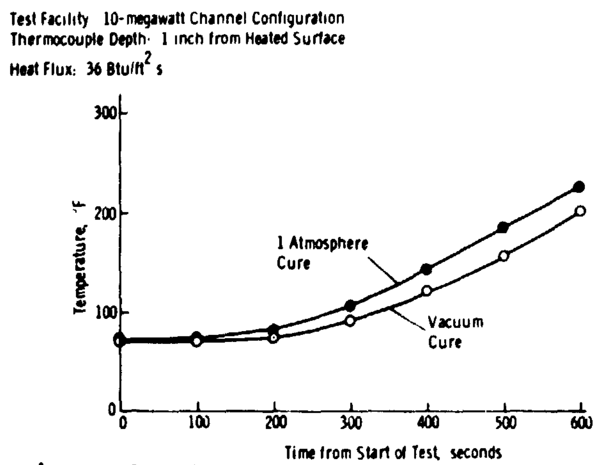


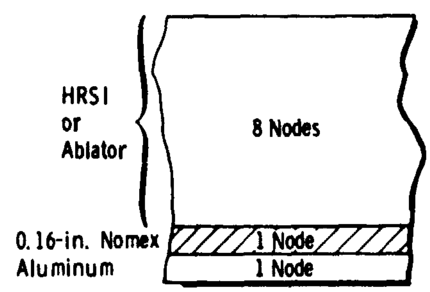
Figure 3.3-10
Effect of Cure Environment on MA 25S Thermal Performance

3.4 ABLATOR THERMAL PERFORMANCE PREDICTIONS

A thermal model was developed to predict the thermal performance of the candidate ablator materials during reentry. The principal output of interest from the model was the maximum temperature of the aluminum structure protected by the ablator. For purposes of comparison, a thermal model was also developed for HRSI. Figure 3.4-1 describes both models.

HRSI Thermal Model

- Used to Provide Flight Baseline Temperatures
- HRSI Thermal Conductivity at 65 psf Used



Ablator Thermal Models

- No Recession Considered
- Existing Virgin Material Thermal Conductivity and Specific Heat Data Used for All Materials
- Char Thermal Conductivity Adjusted to Match Plasma Arc Test Data
  - Indepth Thermocouple Temperature Profiles Matched
- Char Density Deduced from Plasma Arc Test Results

Figure 3.4-1 Ablator and HRSI Thermal Models

As noted in the figure, these models were relatively simple. The ablator model did not consider surface recession and it treated the material essentially as an insulator with a unique set of thermal properties for both the virgin material and the char layer. The virgin material thermal properties were taken from previously established data. Thermal properties of the char layer were deduced from the plasma arc test results. Char layer density was calculated from char depth measurements and pretest and posttest ablator weights. Thermal conductivity was inferred from the indepth thermocouple measurements of the stagnation test specimens. Figure 3.4-2 shows the resulting correlation between the temperature profiles predicted by the analytical model and the indepth thermocouple data. Calculations were not made for SLA 220 since it had already been eliminated as a candidate material. The precured correlation is shown at 400 seconds rather than 600 seconds (end of test) because the 1/2-inch thermocouple data were lost after this time.

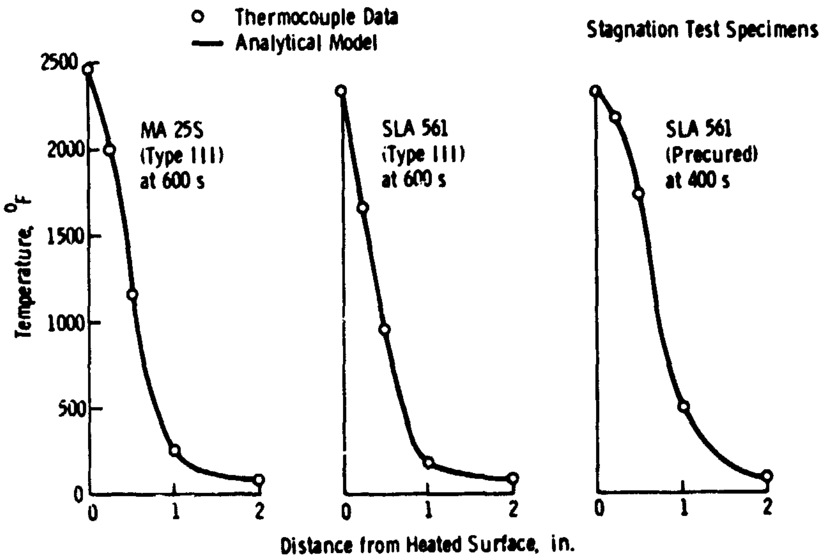


Figure 3.4-2
Comparison of Measured and Predicted Ablator Temperature Profiles

Figure 3.4-3 compares the transient temperature response of HRSI-protected aluminum structure with RI model predictions. The analysis was made for body point 1030. The location is illustrated in Figure 3.4-4. The agreement is considered good in view of the fact that our model used the simplifying assumption that an average reentry pressure of 65 psf can be used to determine the HRSI thermal conductivity. The 15°F difference shown is attributed to our use of a constant-pressure thermal conductivity, whereas the RI model considers a variable-pressure effect on thermal conductivity.

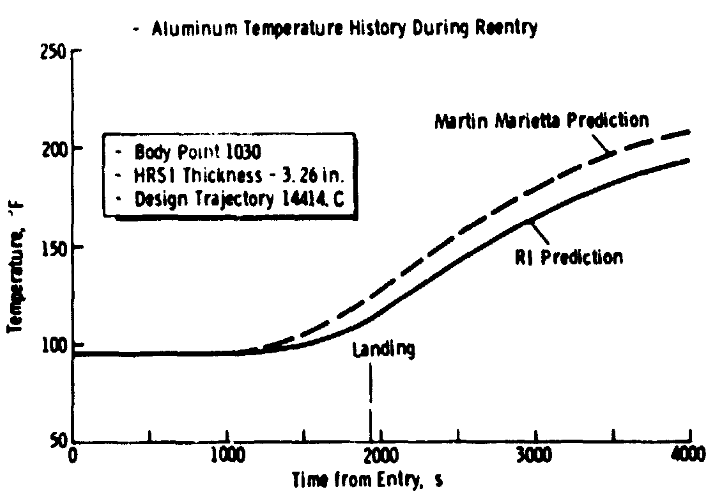


Figure 3.4-3
Comparison of HRSI Thermal Model Predictions

- Initial Temperature of 100°F
- SIP Thickness - 0.16 in.
- Design Trajectory 14414.1C

Body Point	Thickness, in.	Maximum Structured Temperature Rise, °F			
		SLA 561 Type III	MA 25S Type III	SLA 561 Precured	HRSI
1030	3.26	7.4	9.3	93	114
1703	0.81	241	245	282	258
1800	1.0	135	139	227	210
213	3.66	0.1	0.4	6	22

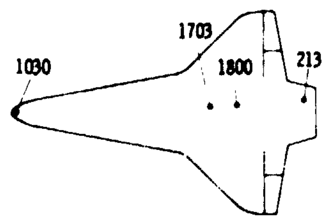


Figure 3.4-4
Ablator Thermal Performance Predictions

Flight predictions were made for ablator-protected and HRSI-protected structure at the four locations shown in Figure 3.4-4. This figure also defines the HRSI and effective aluminum thicknesses at these locations, as well as the corresponding entry heating levels. Results of the flight analysis are given in Figure 3.4-4. The temperatures shown represent the temperature rise above the initial entry temperature used for the analysis, which was 100°F. In these terms, the allowable temperature rise of the structure is 250°F. As noted in the figure, all calculations assumed a SIP thickness of 0.16 inch.

Figure 3.4-4 shows that the temperature rise for both of the cure-in-place ablator candidates is less than for HRSI at all body points and is also less than the allowable temperature rise of 250°F. The temperature, however, approaches the 250° limit at body point 1703. The precured ablator exceeds this limit slightly--by 32°F at body point 1703. It can be kept below the limit if the initial entry temperature is reduced as shown in Figure 3.4-5. This figure shows actual temperatures rather than temperature rise and that a 50°F initial temperature produces the desired 350°F maximum structural temperature. The 50°F initial temperature could be achieved by proper orbiter attitude control prior to reentry. An acceptable temperature can also be reached by utilizing the allowable mold-line tolerance. For example, increasing the 0.81-inch precured ablator thickness by 0.25 inch gives a maximum structural temperature of 332°F at body point 1703.

Another study examined the sensitivity of the ablator thermal performance to entry mission. The results, given in Table 3.4-1, confirm the trends noted in previous ablator studies, i.e., backface temperature is relatively insensitive to total heat load.

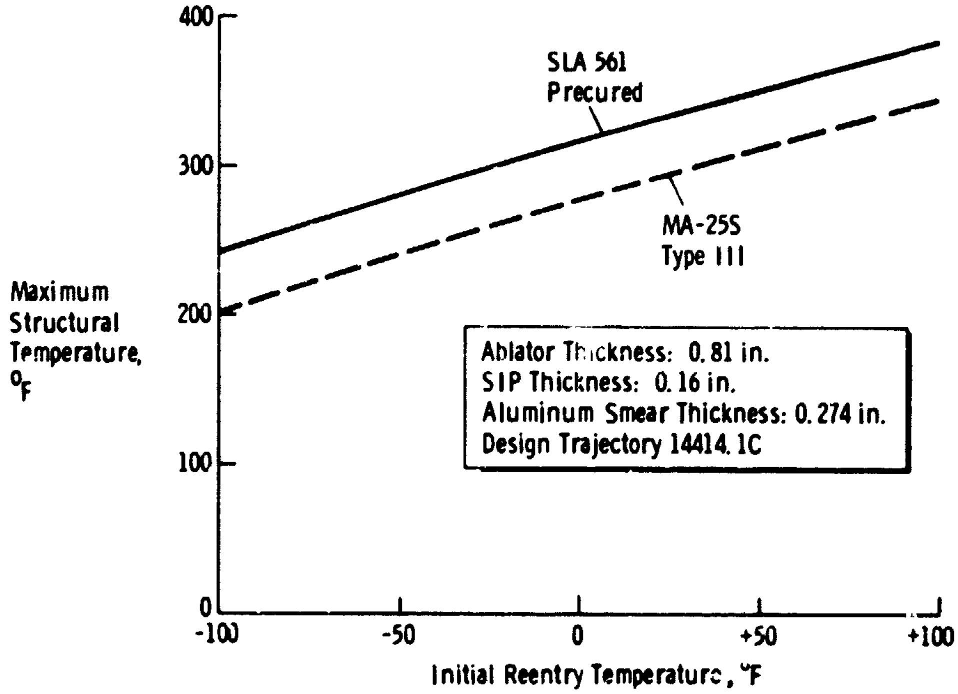


Figure 3.4-5
Effect of Initial Temperature on Ablator Entry Thermal Performance at Body Point 1703

Table 3.4-1
Effect of Mission on Maximum Entry Temperature

- Initial Temperature • 100°F
- SLA 561 Precured Ablator
- Ablator Thickness • 0.81 in.
- Body Point 1703

Mission	Temperature Change, °F*
14414.C Design	0
STS-1 Nominal	-11
STS-1 Load Disperse	+10
STS-1 Rate Disperse	-3

* From 14414.C Design Mission

4.0 OPERATIONAL USE DEFINITION

Definition of the crew operations interfaces was initiated with the review of applicable requirements documentation. The TPS Repair Kit Requirements document, JSC16209 and Preliminary FOD-TPS Repair Kit Operational Requirements document were specifically reviewed.

Repair kit timeline constraints were compiled and sequenced to provide a clear understanding of time-oriented requirements and their effect on the overall mission timeline and repair kit design. Repair kit timeline constraints, given in Table 4-1, are summarized as follows:

1) Crew will not be available for repair kit activities until launch + 5 hours;

2) Crew cabin monitoring will be limited to two to three switch activitations or meter readings not to exceed 10 minutes per crew day;

3) IVA repair kit actions that potentially will enhance or shorten the EVA will be performed within 45 minutes during the first half of the 3-hour EVA preparation time;

4) Time requirements were not specified for payload bay activities;

5) Five areas, with a maximum size of 18x36 inches, can be repaired during a 6-hour EVA;

6) Each repair, from start until assessment completion, will be performed within 45 minutes maximum;

7) Cure-in-place ablator material will reach a gel rate within 15 to 30 minutes after application;

8) Assessment of the repair will not require more than 10 minutes;

9) Cure-in-place ablator material will cure in a minimum of 18 hours preceding start of reentry;

10) Repair kit material will be sufficient to support three 6-hour EVAs.

Analysis of the timeline constraints during the study revealed a minimal number of impacts, as identified in Table 4-2. Solutions indicate the impacts will remain within the overall mission timeline constraints and requirements intent. Enabling of payload bay (PLB) power to support thermal conditioning of the

Table 4-1 Repair Kit Timeline Constraints

Activity				
LAUNCH				
CREW CABIN (FLIGHT DECK) ACTIVITIES START				5 HR
2 to 3 SWITCH ACTIVATIONS OR METER READINGS				10 MIN/DAY
EVA PREPARATIONS START				
REPAIR KIT PREPARATIONS START } IF REQUIRED	45 MIN	1.5 HR	3 HR	
REPAIR KIT PREPARATIONS COMPLETE				
EMU PREPARATIONS START				
EVA PREPARATIONS COMPLETE				
DEPRESS THE AIRLOCK				
REPAIR KIT ACTIVITIES IN PAYLOAD BAY		NO REQ		
START REPAIR ACTIVITY				
REPAIR MATERIAL MIXING				
REPAIR AREA OF 18x36-in. MAXIMUM	30 MIN	45 MIN		
REPAIR MATERIAL REACHES GEL STATE				
ASSESSMENT OF REPAIR START			6 HR	
ASSESSMENT OF REPAIR COMPLETE	10 MIN			
2ND REPAIR SITE		45 MIN		
3RD REPAIR SITE		45 MIN		
4TH REPAIR SITE		45 MIN		
5TH REPAIR SITE		45 MIN		
REPAIR KIT ACTIVITIES IN PAYLOAD BAY		NO REQ		
REPRESS THE AIRLOCK				18 HR
REPAIR MATERIAL CURED				
START REENTRY ACTIVITY				

repair kit stowage container and contents will be required prior to launch + 5 hours. Completion of this function appears possible by the right-seated crewman enabling the necessary switch(es) on orbiter panel R1.

Table 4-2 Repair Kit Timeline Impacts

NO CREW MAINTENANCE / MONITORING UNTIL L+5 HOURS
- Enable PLB Power for Thermal Control via Cabin Panel R1
CAPABILITY OF FIVE 18x36-in. REPAIRS DURING 6-HR EVA
- Repositioning required to support EMU work envelope
- 2 to 3 Large Repair Areas during 6-hr EVA
- Five possible during the Three 6-hr EVAs
15 to 30 MINUTES TO REACH GEL STATE & 10-MINUTE ASSESSMENT OVERLAP
- Significant assessment is OML comparison with surrounding area
- Gel state increases the difficulty to perform further corrective action

Performing five repairs with a maximum size of 18x36 inches during a single 6-hour EVA does not appear feasible. One of two factors, or both, will necessitate division of the repair site into workable task areas. Variations in the cavity depth could range form 1.01 to 3.66 inches, necessitating task buildup for the largest depression or large-volume cure-in-place/exact thickness precured materials to support all possibilities. An EMU work envelope guideline of 12x24 inches will require repositioning to workable task areas or large-volume cure-in-place/rapid application if the envelope is expanded. However, performing two to three large repair areas appears more realistic during a single 6-hour EVA and all five will certainly be possible during three 6-hour EVAs.

Reaching the gel state for cure-in-place material in 15 to 30 minutes and assessment of the repair within 10 minutes are considered overlapping functions and viewed as a single time requirement. The two significant assessment features are comparisons of the gel state and outer moldline (OML) with the surrounding area. The most significant assessment feature is comparison of the OML with the surrounding area and any subsequent corrective actions. Assessment and corrective activities were therefore considered to be a part of the time prior to reaching the gel state (workability). Shorter times to reach the gel state for cure-in-place materials increases the difficulty to perform further corrections of the OML, if required, while longer times require inactive support of small repair areas or sampling techniques to ensure that the gel state has occurred. Preliminary event timelines for the two concepts used in repairing the large work area indicated a gel time of 1 hour to be more desirable. Further definition of task work areas, unit/volume selection and timelines will allow selection of a single gel time that can support both large and small repair areas. After an understanding of the time-oriented requirements was gained, the crew activities were indentified for the crew cabin, middeck, payload bay and repair site. Crew activities for each of these crew stations are summarized in Table 4-3. No repair kit activities that could enhance or contribute to a shorter duration EVA by performing middeck preparations were identified. The middeck crew station was therefore eliminated from further analysis.

Table 4-3 Repair Kit Timeline Activities

CREW CABIN
- 1 to 2 SWITCH ACTUATIONS ON ORBITER PANEL R1 TO ENABLE PLB POWER TO REPAIR KIT THERMAL SYSTEM
- TBD METER READINGS AT INTERVALS DURING EACH CREW DAY (<10 MIN)
MID DECK
- NO REPAIR KIT ACTIVITIES IDENTIFIED THAT WILL ENHANCE OR CONTRIBUTE TO A SHORTER DURATION EVA
PAYLOAD BAY
- MINIMAL EVA TIMELINE ACTIVITY
- UNSTOW, PREPARE & REENTRY STOWAGE
REPAIR SITE
- 45 MINUTES/REPAIR SITE ALLOCATED TO EVA TIMELINE
- INSPECTION OF REPAIR SITE
- AREA PREPARATION/DEBRIS REMOVAL,°IF REQUIRED° USING MAXIMUM OF 2 TOOLS
- UNSTOW REPAIR KIT ITEM(S) NEEDED
- CURE-IN-PLACE ADHESIVE MIXING
- APPLICATION OF ADHESIVE TO: (a) FILL VOID
(b) BOND PRECURED BLOCK(S) & FILL VOIDS
- OML ASSESSMENT USING REQUIRED TOOL
- SUPPORT REPAIRED AREA FOR SUFFICIENT TIME TO ASSESS GEL STATE
- ASSESSMENT OF REPAIR
- STOW ITEM(S) AS NECESSARY FOR TRANSLATION

The timeline constraints and projected crew activities provided the basis for development of an EVA concept, repair approach and preliminary event timeline. Throughout the study these were interactive with repair kit concepts development and tradeoff evaluations in refining the crew/operations interface.

The complete repair EVA concept is summarized in Table 4-4 to provide a basis for the baseline operational use description. The activities shown in bold print represent activities in the EVA where the repair kit design directly affects the tasks and time required of the EVA crewman. The 6-hour EVA begins with the EVA crewman depressing and egressing the airlock. Translation will be made within the payload bay to the TPS repair kit stowage area.

Table 4-4 EVA Concept for MMU

Depress & Egress the Airlock
Translate to Payload Bay Stowage Area
UNSTOW & PREPARE REPAIR KIT
Don & Check Out the MMU
Secure Repair Kit/Work Station to MMU
Egress the Payload Bay
Fly to Repair Site
Attach to the Orbiter
PERFORM REPAIR KIT PREPARATIONS
PERFORM REPAIR
PERFORM REPAIR ASSESSMENT
PERFORM REPAIR KIT STOWAGE
Return Flight to Payload Bay
Repeat the Above Block 4 Times
Remove Repair Kit/Work Station from MMU
Secure MMU
STOW REPAIR KIT
Ingress & Repress the Airlock
Terminate the EVA

TPS repair kit activities commence at this point in the EVA. The TPS repair kit stowage container will be opened, launch restraints removed and repair kit items to support the first planned repair site removed. The doors will then be closed to maintain the thermal environment. Having unstowed and prepared the repair site items onto the work restraint (WR), the EVA crewman will don and check out the manned maneuvering unit (MMU), deploy the WR onto the MMU, egress the PLB, fly to the repair site and attach the MMU/WR to the orbiter.

Repair area preparations will include an inspection of the repair site and preparing the area. Two tools will be provided for this task. Irregular portions of tiles that appear structurally sound will not receive any preparations because our cure-in-place ablator does not need smooth surfaces to adhere.

The site will be repaired using one of three repair techniques--coating repair, cure-in-place ablator application or precured application. Assessment of the repair will consist of determining that the repair is within ± 0.25 inch of the outer moldline using the OML assessment tool and observing that the gel state has occurred. Used repair kit items will be placed in the WR transport container for return flight to the PLB or another repair site.

As additional repair items are required for other repair sites, return flights will be made to the PLB to return used items and obtain the necessary materials to support the next repair site. This repetitive sequence will be performed as many times as the EVA plan specifies. On the last return flight, the WR will be stowed and removed from the MMU and the MMU will be secured and doffed.

The EVA crewman will return to the TPS repair kit stowage container and remove any used items from the WR transport container. The TPS repair kit stowage container will be closed and the launch/reentry EVA latch reengaged. If additional EVAs are planned, the thermal protective edge cover will be pressed back in place.

Translation will be made within the PLB to the airlock. The EVA crewman will ingress and repress the airlock and subsequently terminate the EVA.

Figures 4-1, 4-2, 4-3 and 4-4 and Tables 4-5 and 4-6 provide and overview of our repair approach, stowage container, self-contained unit and three-part unit concepts. Data and significant features for each design concept that support the operational use definitions and the results of our design definition are identified. The results of integrating requirements with design alternatives that offer operational suitability for the repair mission are reflected. Figure 4-5 depicts the four tool concepts defined to support the repair task.

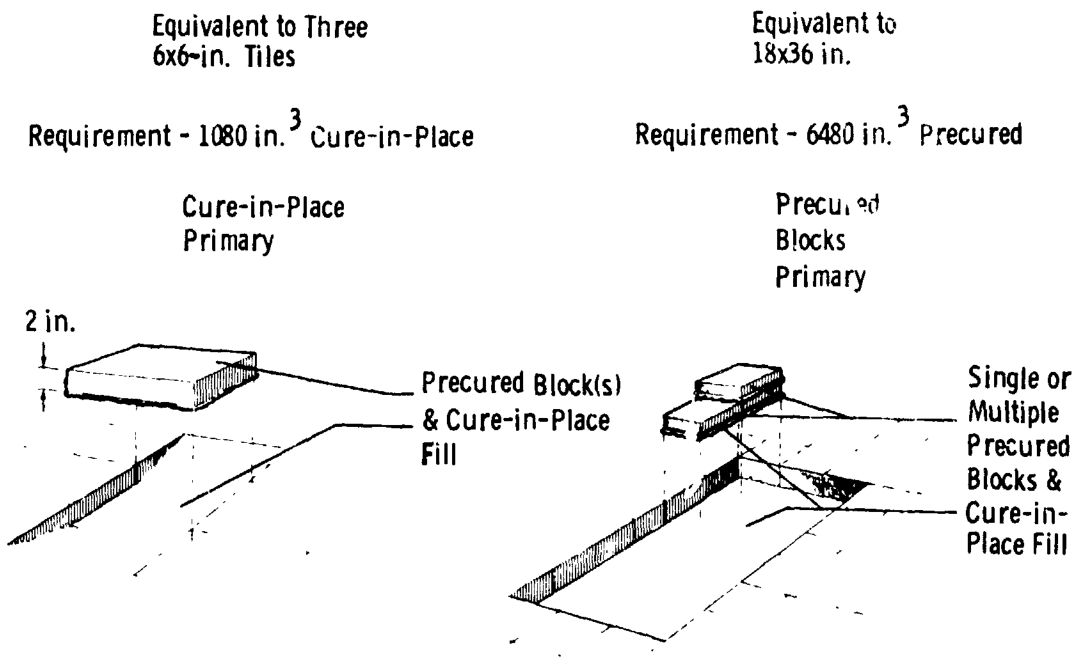


Figure 4-1 Repair Areas

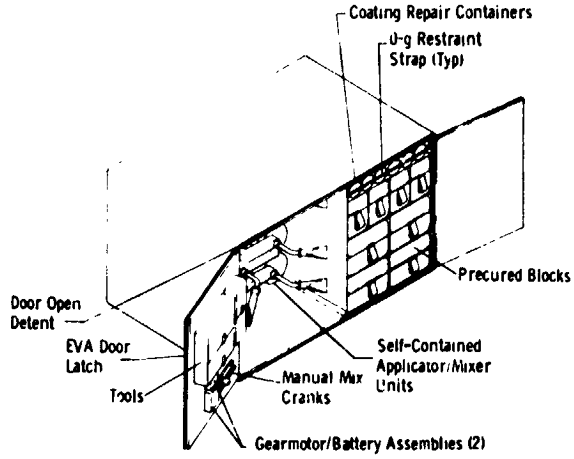


Figure 4-2 Stowage Container

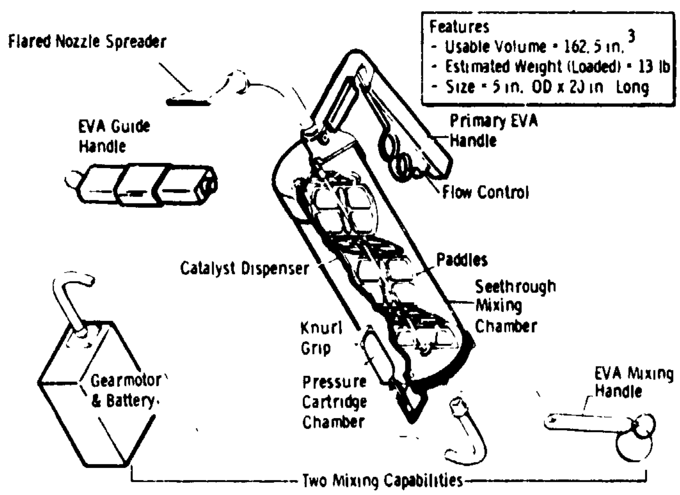


Figure 4-3 Self-Contained Unit

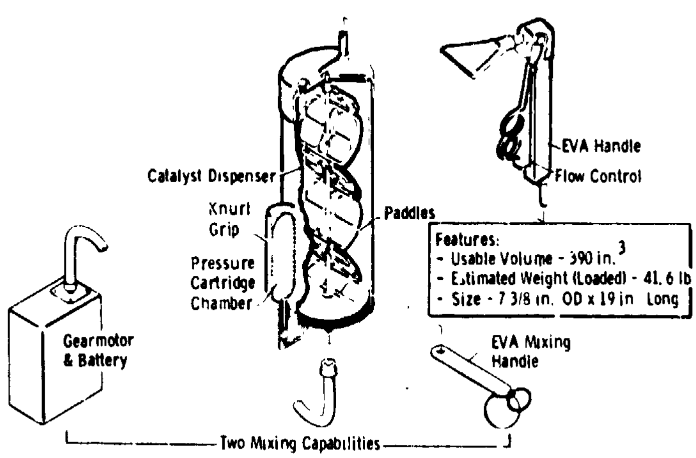


Figure 4-4 Three-Part Unit

Table 4-5
Repair Capabilities - Self-Contained Unit

	Self-Contained Unit		
	Equivalent to Three 6x6x2-in. Tiles		Equivalent to 18x36 in.
	Cure-in-Place Only	Cure-in-Place and Precured	Cure-in-Place and Precured
Repair Sites per Unit	0.75	1	0.5
Repair Sites per Kit	6	8	4
EVA Timeline per Repair Site	28 minutes		60 minutes*
	Stowage Quantities - 8 Units Usable Volume Cure-in-Place - 162.5 in.^{3} per Unit - 1300 in^3 per Kit Volume Precured Blocks - 6534 in^3 - 162 Blocks (64 of 1 1/2, 48 of 1, 50 of 3/4) Flow Rate 21 in.^{3} at 30 psi		
	*Worst case, no MMU/WR reposition.		

Table 4-6
Repair Capabilities - Three-Part Unit

	Three-Part Unit		
	Equivalent to Three 6x6x2-in. Tiles		Equivalent to 18x36 in
	Cure-inPlace Only	Cure-in-Place and Precured	Cure-in-Place and Precured
Repair Sites per Unit	1.8	2-3	1
Repair Sites per Kit	7.2	8-12	4
EVA Timeline per Repair Site	28 minutes (1st) 22 minutes (2nd)		50 minutes*
	Stowage Quantities - 4 Units and 4 Hoses with Nozzles Usable Volume Cure-in-Place - 390 in^3 per Unit - 1560 in^3 per Kit Volume Precured Blocks - 6534 in^3 - 162 Blocks (64 of 1 1/2, 48 of 1, 50 of 3/4) Flow Rate - 21 in^3 at 100 psi		
	*Worst case, no MMU/WR reposition.		

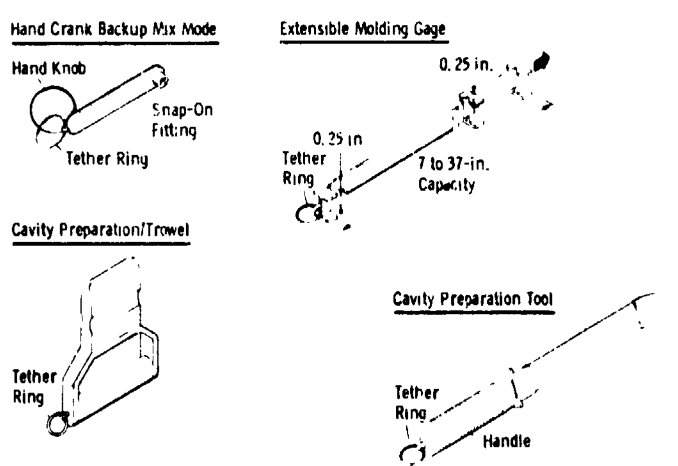


Figure 4-5 Tools

4.1 STOWAGE CONTAINER

The basis for the stowage container design is summarized in Table 4-7. An overview of the stowage container and its significant operational use features is depicted in Figure 4-2. The EVA crewman will lift the thermal protective edge cover by pulling a series of tabs to release the Velcro. An EVA latch will be released and each door will be positioned open (detent design holds door in place). A minimal number of launch restraints will be unlatched (EVA latch), pulled to release and stowed in voids within the applicator/mixer stowage volume. Three thicknesses of precured blocks, soft-packaged to support typical repair sites, and emmittance repair agent spray cans are available in a pantry concept on the right half of the stowage container. Mixer/applicator units are available in a similiar pantry on the left half of the stowage container. Gearmotor/battery assemblies, mixing hand crank and EVA tools to support repairs are mounted (EVA removable) on the left-hand door. EVA soft restraints will maintain the organization within the stowage container and assist in placing used units back into the stowage container. Repair site scenerios developed before flight and refined during and after the inspection EVA will enable the EVA crewman to remove the repair kit items necessary to support large single or multiple small repair sites and place them in the work restraint transport container. The doors will then be closed between uses for thermal protection and maintained closed in orbit by magnetic latches.

Table 4-7 Basis for Stowage Container Design

EVA Foot Restraints Located for Visual and Manipulative Tasks
EVA Removable Front Cover - EVA latching mechanisms - Open front cover restrained to container - Magnetic latches for onorbit use
EVA Removable Interior Launch Restraints - Front plane access - Minimal loose hardware
Repair Site Items Compartmentalized in Stowage Container - Applicator/mixer units - Precured blocks (packed to support typical site) - Tool caddy stowage similar to Shuttle contingency tools - Spray cans
EVA Transfer Bags - Hold repair site items - No onorbit packing required - Front plane access to remove from stowage container - Soft restraint of contents

4.2 PRECURED BLOCK QUANTITY RATIONALE

Our low-density precured ablator material, SLA 561, offers the capability to support a significant total repair area. We have carried our analysis beyond the standard block, 2 inches thick, because the orbiter tile thickness ranges from 1.01 to 3.66 inches (Fig. 4-6). We chose the 18x36-inch (3x6 tiles) as the probable maximum repair site size and assumed that any bonding layers of cure-in-place ablator would require approximately 0.2 inch of thickness for each layer of precured blocks. The result of our analysis revealed a combination of three thicknesses (0.75, 1.0, 1.5 in.) provides the capability to support repair areas in the entire range of thicknesses with minimum layer building required. This analysis is summarized in Table 4-8 and contains recommended proportional quantities for the three thicknesses necessary to meet the 6480 in.^{3} requirement. The usable volume of cure-in-place ablator we have provided supports this recommendation. Partial/irregular tile repair will be provided for by either prescoring several of the blocks or precutting several blocks into random sizes (e.g. 4x2, 3x3, 2x2, etc).

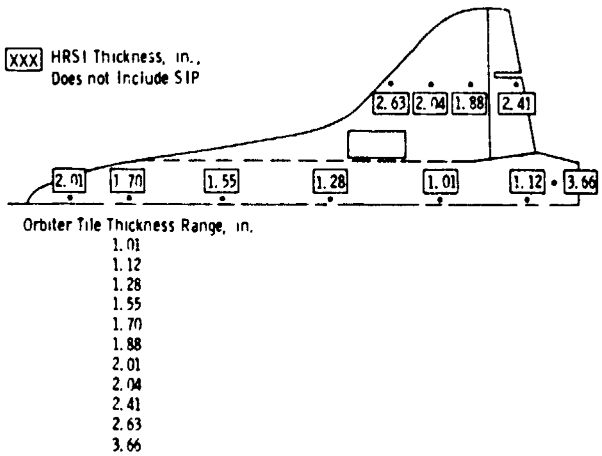


Figure 4-6 External Insulation Thickness

Table 4-8
Precured Quantity Analysis Summary

Orbiter Tile Thickness, in	Specification Area, 18x36 in. (3x6 Tile Array) Precured Blocks, in., with 300 in ^{3}, Cure-in-Place	Recommended Precured Blocks Quantity, No./Thickness	Volume, in.^{3}	Weight, lb*
1.01	18 of 3/4			
1.12	18 of 3/4			
1.28	18 of 1			
1.55	18 of 1	50 of 3/4		
1.70	18 of 1 1/2	48 of 1	6534	49.2
1.88	18 of 1 1/2	64 of 1 1/2		
2.01	18 of 1 1/2			
2.04	18 of 1 1/2			
2.41	36 of 1			
2.63	36 of 1			
3.66	36 of 1 1/2			

*Assumes 13 lb/ft^3 for precured blocks

4.3 APPLICATOR/MIXER UNIT

An overview of these units and their respective operational use features is depicted in Figures 4-3 and 4-4. The self-contained unit and three-part unit are each operationally suitable for an EVA crewman to perform two primary functions: (1)mixing of the cure-in-place ablator material, and (2)application of the cure-in-place ablator to fill a void or form a bonding layer(s)-. The numerous tradeoffs for crew use optimization evaluated in arriving at the recommended design are summarized in Table 4-9.

Table 4-9
Applicator/Mixer Unit Tradeoffs for Crew Use Optimization

Eliminate Manual Action for Expulsion - Continuous pressure to aft of diaphragm
Provide Flow Rate Control for Expulsion - Real-time open/flow control/close capability
Increase Confidence of EVA Cure-in-Place Mixing - Dispense catalyst over cartridge length - Eliminate pressurization system for catalyst expulsion - Primary and backup mixing capability - Catalyst dye visual cue - Wipers to eliminate capillary attraction
Minimize Applicator/Mixer Unit Size for Application Task - Primary and backup mixing hardware removable - Usable volume vs workable volume vs stowage volume - Unit orientation relative to EVA crewman and repair site
Integrate Aids into Concept - Spreading capability with flared-end nozzle - One-hand operational use capability - Second-hand guide assist handle - Extension for increased visibility and cavity depth access

The orbit mixing function of the cure-in-place ablator must occur if repair activities are to be successful. Therefore we have provided a redundant means to complete the mixing function and a visual indication for the EVA crewman.

It is extremely important that the EVA crewman be provided a visual cue that mixing has been accomplished rather than finding that gel has not occurred after completing the repair. The MA 25S cure-in-place ablator offers the capability to produce this visual cue because the mixed material contains ferric oxide, which is seen as a reddish hue. Ferric oxide mixed in a normally white resin produces the reddish hue. Housing the ferric oxide with the catalyst provides a positive indication of catalyst dispersion and material mixing. The catalyst further has the property of migration beyond that of the ferric oxide even in a vacuum.

Nominal mixing will be performed immediately following repair site preparations to maximize the time available to use the predetermined work life of the cure-in-place ablator. The EVA crewman will remove either unit from the work restraint transport container, attach a tether to the thether ring and place it nozzle end down in a mixing holder. Nominal mixing will be accomplished using a gearmotor/battery assembly and a manual mixing capability is provided as a backup. A spare gearmotor/battery assembly is also available in the TPS repair kit stowage container as well as the backup manual hand crank. A swing-in-place mixing holder device mounted on the WR will eliminate the need for the EVa crewman to hold the unit and overcome rotational movement. The EVA crewman will then attach (EVA snap-on/off) the flexible drive shaft from the gearmotor/battery assembly, also mounted on the holder, to the aft end of either unit. The gearmotor/battery assembly will be engaged (EVA on/off switch) for a period of 3 minutes to achieve mixing. The initial rotary motion of the mixing paddles fractures the catalyst holder, dispersing the catalyst over the entire cartridge length.

Our current mockup has a seethrough cartridge for the mixing visual cue. However, as mixing confidence is demonstrated, a simple visual obeservation of the ablator material as it is dispensed may prove sufficient.

The mockup was used to demonstrate mixing numerous times and one time with actual catalyst. The results of the cured material are shown in Table 4-10.

Table 4-10
Functional Mockup Demonstration of MA 25S

- Mixed and Applied MA 25S with Functional Mockup
- Poured Four 1x3x3-inch Blocks
- Gel Time Approximately 60 minutes
- Test Data:

	Shore A Hardness	Bond Tension, psi
1st Block	35-40	51
4th Block	35-40	65

4.3.1 Self-Contained Unit

The EVA crewman will remove the self-contained unit and swing the mixing holder device out of the way. One turn of the pressurization cartridge punctures it and applies pressure to the piston. The cure-in-place ablator to fill a void or form a bonding layer can be applied using one hand. The EVA primary handle, held in either hand, also contains the on/off and flow control for the unit. Two pounds of force applied to the trigger opens the flow and a deflection of 15 degrees produces a maximum flow rate. Spring force decreases or turns off the flow as the EVA crewman releases grip force.

Additional stability during ablator application is available using an optional second hand guide handle, which is EVA attachable (snap on/off) to either side at right angles to the primary handle. Placing the second handle close to the primary handle minimizes the distance between hands, maximizing efficient use within the two-hand reach envelope. The second hand guide assist is stowed as a tool using the EMU miniwork station tool caddy concept.

The end nozzle is flared to provide an assist in spreading the cure-in-place ablator material as well as a clean cutoff capability. The nozzle is extended at an angle to provide maximum visibility to the EVA crewman and extension to the bottom of a 4-inch cavity.

The usable volume of 162.5 in.3 provides the capability to fill a volume equivalent to 2 1/4 tiles of the 6x6x2-inch size or one-half of an 18x36-inch area when used with precured blocks.

The features of the self-contained unit have changed since the midterm review, from the functional mockup to recommended design. These features are summarized in Table 4-11.

Table 4-11 Self-Contained Unit Design Progress

	Midterm/ Envelope Mockup	Functional Mockup	Recommended Design
Size	4 in. OD x 25 in. Long	4.25 in. OD x 20 in. Long	5 in. OD x 20 in. Long
Weight (Loaded)	8.3 lb	6.9 lb	13.0 lb
Useable Volume	100 in.^{3}	72 in.^{3} (68 in.^{3})	162.5 in.^{3}
Operating Orientation	Horizontal	Vertical	Vertical
One Hand Operation	No	Yes	Yes
Catalyst Dispensing	Entire Length Pressure Injection	Entire Length Housing Fracture	Entire Length Housing Fracture
Mixing Design	Paddles	Paddles with Wipers	Paddles with Wipers
Mixing Method	Optional - Hand Crank with Handle - Gear Motor/ Battery	Primary - Gear Motor/Battery Backup - Hand Crank with Knob	Primary - Gear Motor/Battery Backup - Hand Crank with Knob
Mixing Time	3 min	3 min	3 min
2nd Hand Guide	One Side, Required EVA Snap On/Off	One Side, Required EVA Snap On/Off	Either Side, Optional EVA Snap On/Off
Flow Control	90° Rotation 2nd Hand Guide	90° Rotation 2nd Hand Guide	15° Trigger Pull Primary Handle
Flow Rate	No Prediction	0-21 in.^{3}/min at 30 psi	0-21 in.^{3}/min at 30 psi
Spreader and Clean Cut Off	Flared Nozzle	Flared Nozzle	Flared Nozzle

4.3.2 Three-Part Unit

After completing the mixing function, the EVA crewman will remove the mixing asembly for the three-part unit and swing the mixing holder device out of the way. The hose and one-hand applicator assembly will be removed from the WR transport container and attached (EVA snap-on/off) to the forward end of the mixing container. One turn of the pressurization cartridge punctures it and applies pressure to the piston.

The cure-in-place ablator to fill a void or form a bonding layer can be applied using one hand. The EVA handle, held in either hand, also contains the on/off and flow control capability for the unit. Two pounds of force applied to the trigger opens the flow and a deflection of 15 degrees produces a maximum flow rate. Spring force decreases or turns off the flow as the EVA crewman releases grip force.

The end nozzle is flared to assist in spreading the cure-in-place ablator material as well as provide a clean cutoff capability. The nozzle is extended at an angle to provide maximum visibility to the EVA crewman and extension to the bottom of a 4-inch cavity.

The usable volume of 390 $in.^3$ provides the capability to fill a volume equivalent to 5.4 tiles of the 6x6x2-inch size or one 18x36-inch area when used with precured blocks

4.4 TOOLS

Four tools were defined to support repairs: (1)cavity preparation tool, (2)cavity preparation/trowel tool, (3)OML assessment tool, and (4)the optional second hand assist handle for the self-contained unit. The JSC tool caddy concept developed for the EVA contingency tools will be used for packaging, use and stowage. Two tools per caddy and two caddies will be placed on the EMU miniwork station.

4.5 EVA TIMELINE

Two preliminary timelines (Tables 4-12 and 4-13) were prepared for the typical repair sites--three 6x6-inch tiles and an 18x36-inch tile area. The timelines reflect the events at a single repair site.

Several significant factors, primarily dependent on repair area size and cure-in-place work life, that affect the validity of these or future timelines are.

1) Inspection and preparation will not be known until the EVA crewman arrives at the repair site;

2) Usable cure-in-place volumes that can complete one-half to all of the worst-case repair areas can also complete multiple areas where minimum damage exists, providing translations/attachments can be completed;

3) The rate of dispensing depends on flow rate selection and visual/manipulative capabilities achieved by WR positioning;

4) Gel state assessments will require the EVA crewman to support a single repaired area, assess the last of multiple repair sites or maintain/log samples of various repair sites.

Table 4-12
Event Timeline for Three-Tile Specification Area (Worst Case)

EVENT		Minute	Minute
	Position & Attach for Three-Tile Task Area	Start	
1.	Visually Inspect Damage Area & Surfaces	0.5	
2.	Remove Loose Debris by Hand & Place in MWS Trash Bag	0.5	
3.	Remove Damaged Portions with Either Tool & Place in MWS Trash Bag	2	
4.	Swing Mixing Holder in Place (Attached to Work Restraint)	0.2	
5.	Unstow Applicator/Mixer Unit & Place in Holder	0.5	
6.	Attach Mixing Option to Gun	0.2	
	a) Gearmotor/Battery Assembly Mounted on Mixing Holder		
	b) Hand Crank Tethered on Tool Caddy		
7.	Unlock Paddles & Mix Cure-in-Place Until Visually Acceptable	3	
8.	Remove Mixing Option from Unit	0.2	
9.	Remove Unit & Attach Tethered 2nd Hand Guide (on Tool Caddy)	0.2	
10.	Swing Mixing Holder Out of Way	0.2	
	Cumulative Repair Time		7.5
11.	Turn Pressurization Cartridge One Turn to Enable	0.5	
12.	Apply Cure-in-Place & Precured (As Necessary) to Fill Void	12	
13.	Assess Whether OML Is ± 1/4 in to Adjacent Area with OML Tool	1	
14.	Spread Cure-in-Place As Required	As Req'd	
15.	Reassess OML As Required	As Req'd	
	Proceed to 2nd Repair Site If Volume Remaining & Work Life Permit	--	
16.	(Vent Unit If Required for Reentry Stowage)	TBD	
17.	Remove 2nd Hand Guide	0.2	
18.	Stow Used Unit	0.5	
	Cumulative Repair Time		21.7
19.	Support Repaired Area for Sufficient Time to Assess Gel State	5	
20.	Assess Gel State by Observing Workability	1	
	Cumulative Repair Time		27.7

Table 4-13
Event Timeline for 18x36-in. Specification Area (Worst Case)

	EVENT	Minute	Minute
	Position & Attach for 1st Portion of 18x36-in. Task Area	Start	
1.	Visually Inspect Damaged Area & Surfaces	0.5	
2.	Remove Loose Debris by Hand & Place in MWS Trash Bag	0.5	
3.	Remove Damaged Portions with Either Tool & Place in MWS Trash Bag	2	
4.	Swing Mixing Holder in Place (Attached to Work Restraint)	0.2	
5.	Unstow Applicator/Mixer Unit & Place in Holder	0.5	
6.	Attach Mixing Option to Gun	0.2	
	a) Gearmotor/Battery Assembly Mounted on Mixing Holder		
	b) Hand Crank Tethered on Tool Caddy		
7.	Unlock Paddles & Mix Cure-In-Place Until Visually Acceptable	3	
8.	Remove Mixing Option from Gun	0.2	
9.	Remove Unit & Attach Tethered 2nd Hand Guide (on Tool Caddy)	0.2	
10.	Swing Mixing Holder Out of Way	0.2	
	Cumulative Repair Time		7.5
11.	Turn Pressurization Cartridge One Turn to Enable	0.5	
12.	Apply 0.2-in. Bond Layer of Cure-in-Place to Task Area	5	
13.	Unstow Precured Blocks & Place in Void	3	
14.	Apply Cure-in-Place to Fill Gaps & Form 2nd 0.2-in. Bond Layer	5	
15.	Unstow Precured Blocks & Place in Void	3	
16.	Apply Cure-in-Place to Fill Remaining Gaps	3	
	Cumulative Repair Time		27.0
17.	Assess Whether OML Is ± 1/4 in. to Adjacent Area with OML Tool	1	
18.	Push Down Precured Blocks As Required	As Req'd	
19.	Spred Cure-in-Place As Required	As Req'd	
20.	Reassess OML As Required	As Req'd	
21.	(Vent Gun If Required for Reentry Stowage)	TBD	
22.	Remove 2nd Hand Guide	0.2	
23.	Stow Used Unit	0.5	
	Cumulative Repair Time		28.7
	Detach, Reposition & Attach for 2nd Portion of 18x36-in. Task Area	5	
	Repeat Steps 1 thru 23 Above	28.7	
	Assess Gel State by Observing Workability	1	
	Cumulative Repair Time		58.4
	Cumulative Site Time		63.4
	Three-Part Unit Concept Delta		
	Eliminate 2nd Mixing (Steps 4 thru 11)	⟨5.0⟩	
	Cumulative Repair Time		53.4
	Cumulative Site Time		58.4

5.0 PACKAGING DEFINITION (CONTAINERS AND ELEMENTS)

5.1 REQUIREMENTS

The major requirements include:

1) Any necessary catalyst or hardener must be mixed with the base ablation polymer and the mixed material extruded into the repair area;

2) Must be designed for use by suited crewmember;

3) Must be functional in vacuum conditions;

4) Must not obscure crewmembers' view of cavity;

5) Must provide variable and controllable flow rates;

6) Have clean cutoff characteristics;

7) Must be functional in temperature range of 40 to 125°F;

8) Must be designed so crewmember and equipment are not contaminated with repair material;

9) Must maintain repair materials and equipment in optimum working temperature range throughout repair;

10) Have self-contained unit concept and a three-part unit concept;

11) The minimum cure-in-place ablator volume must be 1080 in.^{3} per kit.

The container must:

1) Provide adequate environment and storage for all repair materials;

2) Have a maximum volume of 12 ft.^{3};

3) Have a maximum weight when loaded of 300 lb;

4) Incorporate a package compatible with the reach capability of a suited crewmember;

5) Provide the restraints necessary for zero-g use;

6) Incorporate heaters able to maintain repair materials at optimum working temperature;

7) Have a thermal blanket configuration the same as the multi-layer insulation used for the orbiter payload bay;

8) Have heaters with an on/off control switch in the orbiter crew compartment and dual monitoring instrumentation to the crew compartment and telemetry to the ground;

9) The minimum precured ablator volume must be 6480 $in.^3$ per kit.

The TPS flight repair kit interface requirements are:

1) Use Shuttle payload bay environments defined in JSC 07700 Volume XIV of the Space Shuttle Payload Accommodation;

2) Use Thermal entry environments defined in Space Shuttle Orbiter Entry Aerodynamic Heating Data Book SD73-SH-0184, Rev C, Book 1, October 1978;

3) Stowage container to ancillary equipment stowage assembly (AESA),

   a) Electrical,
   b) Instrumentation,
   c) Mechanical and structural;

4) Repair kit items to work restraint transport container;

5) Tools to EMU miniwork station;

6) TPS repair kit to vertical installation common ground handling equipment.

5.2 APPLICATOR/MIXER BASELINE DESIGNS

5.2.1 Self-Contained Concept

The proper size and number of applicator/mixers was selected by trading off the EVA handling and time constraints, the volume limitations for the assembly, and the astronaut evaluations in zero-g aircraft. The baseline size applicator/mixer selected is shown in Figure 5-1. This concept is sized for eight units packaged in the TPS repair kit container. The unit is loaded with 185 $in.^3$ of MA 25S material, while the usable ablator is 162.5 $in.^3$. The total usable cure-in-place ablator in the kit is 1300 $in.^3$.

The self-contained applicator/mixer concept as shown in Figure 5-2 is a 5-inch-diameter (outer moldline), 20-inch-long unit. The mixing paddles are a foldable configuration that collapses with the expulsion piston shown. The catalyst tube shown within the ablator reservoir is a glass tube with A 1100 catalyst along with ferric oxide in a carrier loaded within and sealed. The glass tube is supported at the ends by sockets with RTV bond-shock absorber. The mixing paddles are locked in position to prevent paddle rotation until the mixing operation is initiated. The cure-in-place ablator is mixed by snapping on the flexible drive shaft on the battery-operated gearmotor. The paddle lock is released and the drive motor turned on. The paddles turn and break the thin-walled glass tube, which starts mixing with a linear distribution of catalyst and ferric oxide. The exit port will contain a screen to prevent large pieces (1/4 in.) of glass from plugging the outlets. The mixing is completed in approximately 3 minutes. The gearmotor is turned off and the drive shaft released.

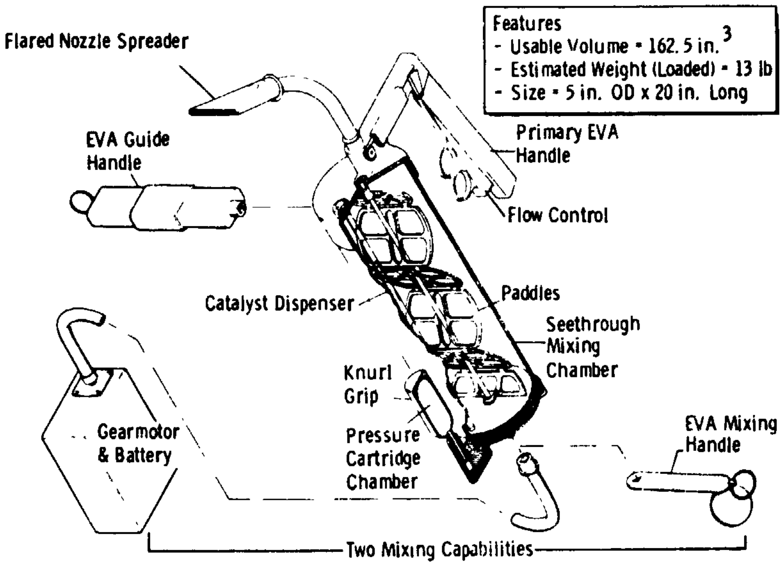


Figure 5-1 Self-Contained Unit

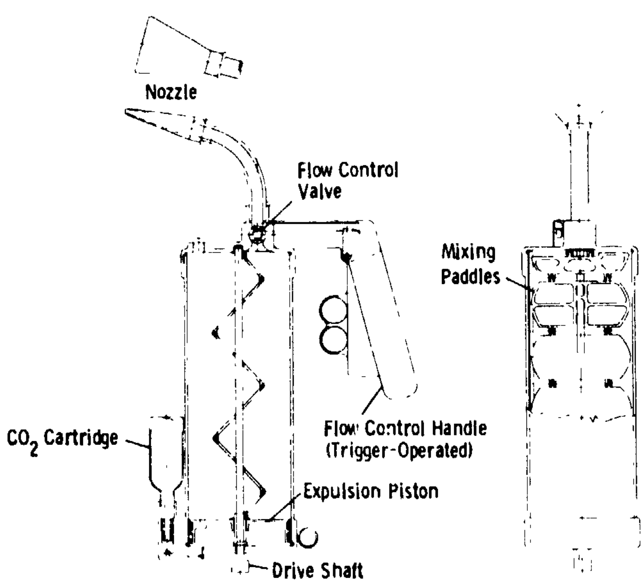


Figure 5-2
Applicator/Mixer Baseline, Self-Contained Unit

The ablator expulsion system is a piston driven by CO_2 gas. The gas is contained in a separate cartridge that is turned one rotation to pierce the seal and pressurize the reservoir behind the piston. The forward handle contains the handgrip trigger that controls the flow rate. The rate is continuously variable from full off to full on. The exit port in the forward applicator/mixer cap is offset from the centerline by 0.85 inch, which allows the paddle shaft to be mounted in the forward cap. The burst diaphragm is shown in Figure 5-2. This diaphragm is burst by the pressure and allows the flow to proceed along the exit tube, which bends 75 degrees away from the handle side. A 2 1/2-inch wide nozzle with a 0.20-inch slot opening is the exit. The nozzle and handle arrangement allows good EVA handling and visibility to the nozzle application area by the astronaut. Two-hand operation is possible by use of a snap-on handle that can be snapped on either side for left- or right-handed operation. One-hand operation is useful for long reach areas to the left or right.

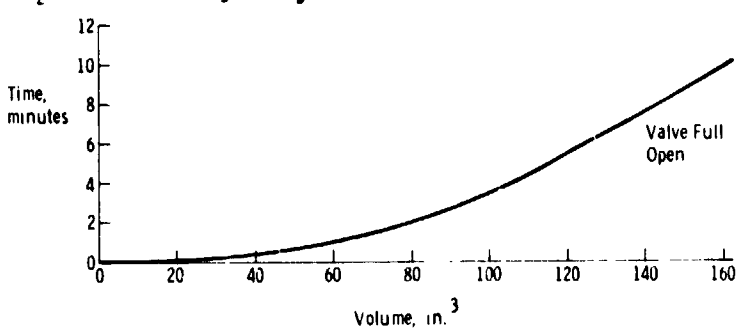
A backup mixing operation is possible by a hand crank tool that takes longer to accomplish complete mixing.

The weight statement for the self-contained concept is shown in Table 5-1. The expulsion time is shown in Figure 5-3.

Table 5-1
Applicator/Mixer Self-Contained Weight Statement

Item	Weight, lb
Hand Flow Control Assembly	1.72
Cylinder	2.30
Forward Cap	0.78
Aft Cap	0.77
Control Valve	0.18
Nozzle	0.19
Expulsion Diaphragm	0.31
Mixing Paddles	0.27
Shaft & Fitting	0.22
Pneumatic Cylinder	0.40
Contingency, 10%	0.72
Dry Weight	7.86
Unusable	0.56
Usable Ablator	4.61
Loaded Weight	13.03

Figure 5-3
Expulsion Time, Self-Contained Unit



5.2.2 Three-Part Concept

The three-part concept is made up of a mixing container, 1.5-meter feedline and a one-hand-operated flow control application unit with spreading nozzle. The mixing container is housed in the MMU work restraint container during application by the one-hand unit. The mixing container is similar in concept to the self-contained mixer concept except for size. The three-part concept is shown in Figures 5-4 and 5-5. The feedline snaps on to the mixing container with a quick-disconnect fitting. Four mixing pots are contained in the TPS repair kit container as well as four feedline hand applicator/spreader assemblies. The mixing pots have a 7.75-inch outside diameter and are 10.0 inches long. The usable ablator is 390 in.^{3} per unit, or a total of 1560 in.^{3}.

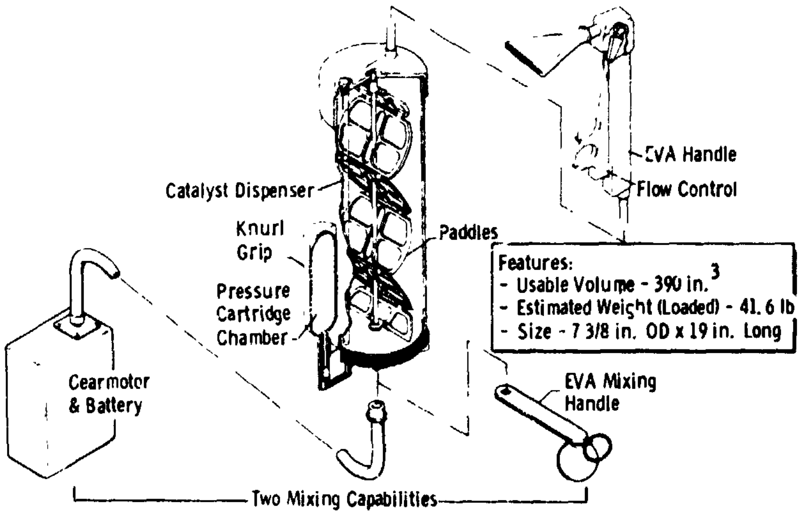


Figure 5-4 Three-Part Unit

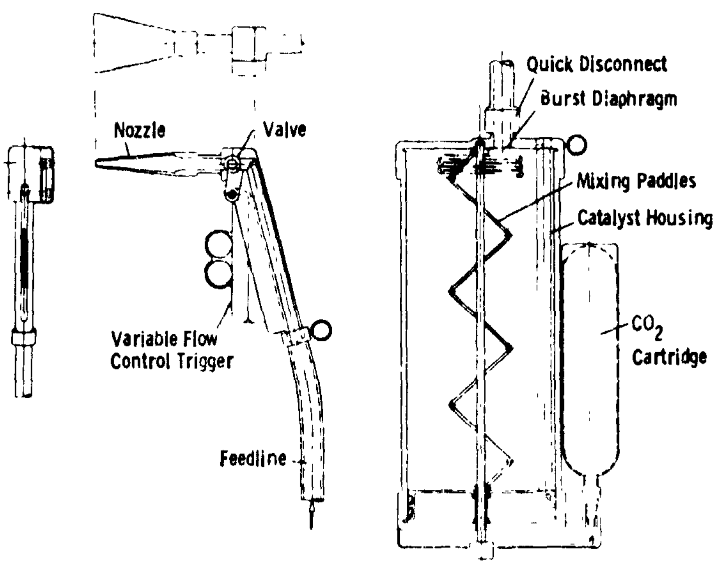


Figure 5-5
Applicator/Mixer Baseline, Three-Part Concept

The one-hand applicator is small and easy to operate with a 3-foot long feedline coming up from the pot. The feedline ID is 0.75 inch and the resulting flow rate is illustrated in Figure 5-6. This is for the 3-foot long feedline plus the hand control unit as shown in Figure 5-4.

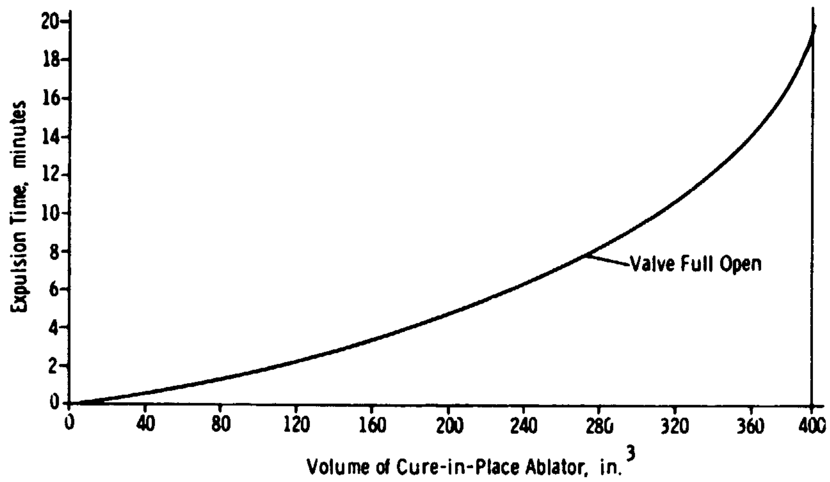


Figure 5-6 Expulsion Time, Three-Part Concept

The operating pressure selected for the three-part concept is a blowdown system operating from 485 to 59 psi and is supplied by a CO_2 cartridge.

The functional mockup of the self-contained unit was modified to operate as the three-part concept by adding a 3-foot feedline with a trigger flow control hand applicator unit.

The weight statement for the three-part concept applicator/mixer unit is shown in Table 5-2. Expulsion time for the three-part unit is shown in Figure 5-6.

Table 5-2
Applicator/Mixer Weight Statement,
Three-Part Concept

Item	Weight, lb
Cylinder	6.6
Forward Cap	4.9
Aft Cap	5.0
Hand Control	1.65
Nozzle	0.19
Expulsion Diaphragm	0.70
O-Rings	0.04
Mixing Paddles	0.57
Catalyst Housing	0.03
Shaft	0.55
Feedline	3.2
Pneumatic Cylinder	1.5
Contingency (10%)	2.5
Dry Weight	27.43
CO_2	0.35
Unusable Ablator	2.75
Usable Ablator	11.06
Loaded Weight	41.6

5.2.3 Design and Stress

The self-contained and three-part concepts of the applicator/mixer are similar in operation. Mixing torque for the paddle concept shown is low (e.g., 20 in.-lb for 60 rpm on the functional mockup). The torque is transmitted to the paddles at both the front and rear attachment connections.

The mixing torque is within reason for the backup mode hand crank operation. The hand crank tool is a 4.5-inch radius direct-drive tool offering a 22.5-in.-lb torque capability with a 5-lb hand force.

The gearmotor selected for the automixing mode is a TRW Globe gearmotor with 77 in./lb of torque at 50 rpm using an Eagle-Pitcher silver-zinc battery.

The pressure expulsion system on the baseline self-contained concept uses a CO_2 cartridge with a blowdown pressure system operating from 150 to 15 psi.

The pressure expulsion system for the baseline development three-part concept uses a CO_2 cartridge with a blowdown pressure operating from 485 to 59 psi.

All units subject to pressure are designed to a factor of safety of 4 on yield strength.

5.2.4 Thermal Control

The thermal control criterion for the applicator/mixer is to maintain the cure-in-place ablator material at a temperature within a gel temperature range of 0 to 125°F. We assumed that the applicator/mixer will be exposed directly to the space environment for a period of up to 1 hour, which is the maximum gel time requirement for the ablator. We also assumed that extra applicator/mixers not being used for the immediate repair job would be stored in an insulated storage box on the work platform. Spare or extra applicators could be exposed to the space environment for up to the 6-hour maximum EVA period.

Since power is not readily available to heat the applicator/mixer, the thermal control approach investigated was to determine whether the heat capacity of the units, combined with low emittance/absorptance coatings, would be sufficient to limit the transient temperature change to acceptable values. Several transient thermal models were constructed to evaluate the thermal response of various components of the applicator/mixer.

The most critical component is the one with the least heat capacity. Examination of both the self-contained and three-part concepts indicated that the feedline of the three-part applicator/mixer has the least thermal mass. Hot (full continuous sun) and cold (-460°F) cases were considered. The transient temperature response for these cases is shown in Figure 5-7.

Wrapping aluminized mylar tape around the feedline limits the temperature change of the feedline to ±27°F for a 1-hour EVA time. Note that the hot and cold cases cause the same absolute temperature change from the initial temperature. This led to the selection of an average of the gel temperature limits [(0 + 125)/2 = 63°F] as a desired storage temperature in the payload bay storage container. Use of an average temperature allows the maximum temperature excursion for both the hot and cold EVA design cases.

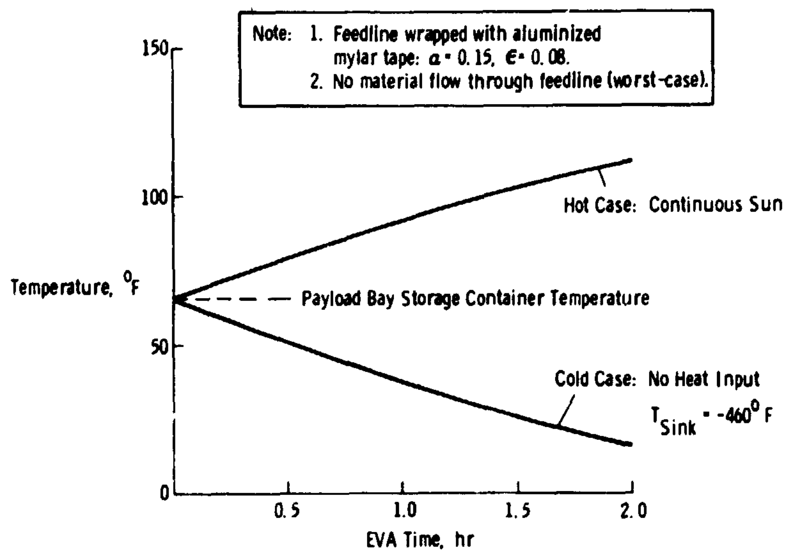


Figure 5-7
Transient Temperature Response to EVA Thermal Extremes

Other applicator/mixer components will experience a smaller temperature excursion for comparable EVA times because of their greater thermal mass. This assumes of course that they are covered with a suitable radiation coating, either in the form of paint or pressure-sensitive films. The only exception would be the transparent section of the cylinder of the self-contained applicator/mixer. If a transparent cylinder is used, the ablator material will radiate heat at a much higher rate. The cooldown characteristics of the ablator for this situation were analyzed assuming an ablator emissivity of 0.80. This analysis also required a knowledge of the thermal conductivity of the uncured MA 25S. An estimate of the uncured thermal conductivity was made by a simple test. The uncured material was placed in a 3-inch diameter 6-inch high thin wall (0.01) steel can. The can was then taken from a uniform room temperature condition and placed in a freezer at 0°F. The transient response of a thermocouple at the center of the material in the can was monitored. A closed-form analytic solution for a cylinder suddenly placed in a different temperature environment was then evaluated to determine the thermal conductivity required to match the thermocouple data. A thermal conductivity of 0.04 Btu/ft-h°F resulted. This is slightly lower than the 0.052 listed for the original MA 25S with 652 resin at 60°F. As a result of this test, the uncured MA 25S thermal conductivity was conservatively assumed to be the same as for the cured material.

The results of the analysis are given in Figure 5-8. Both the minimum and average temperatures are shown. A 1-hour exposure causes a minimum temperature of 0°F although the average temperature is 30°F. Use of an opaque cylinder wall would reduce this temperature drop by allowing the use of a lower emmittance coating on the cylinder.

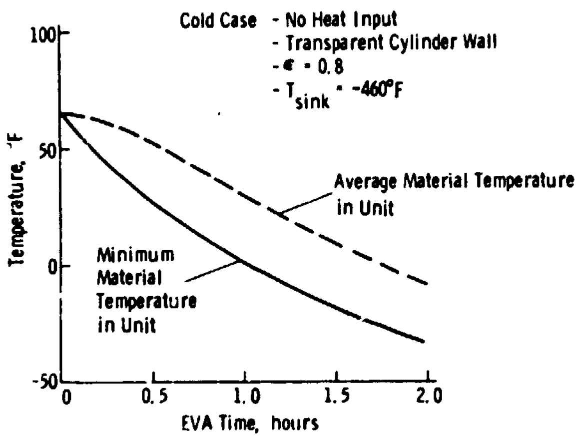


Figure 5-8
Transient Temperature Response
of Ablator Material to EVA Cold Case

An additional analysis considered the temperature change in the self-contained applicator/mixer when stored in a storage bag on the work platform. It was assumed that the bag consisted of 10 alternating layers of aluminized mylar separated by dacron net. It was also assumed that the bag was covered with a high-emissivity (0.9) cloth cover to protect the mylar from tearing. Figure 5-9 shows the temperature change for a cold case. Two effective emissivities are shown, with the higher value of 0.04 considered to be a realistic design condition. The figure shows that applicator/mixers stored in an insulated bag remain within acceptable temperature limits during a full 6-hour EVA period. As a result of the analyses conducted during Phase I, no major thermal control problems are anticipated for the applicator/mixer.

Temperature Response of Applicator/Mixer in Insulated Transport Container During EVA Exposure

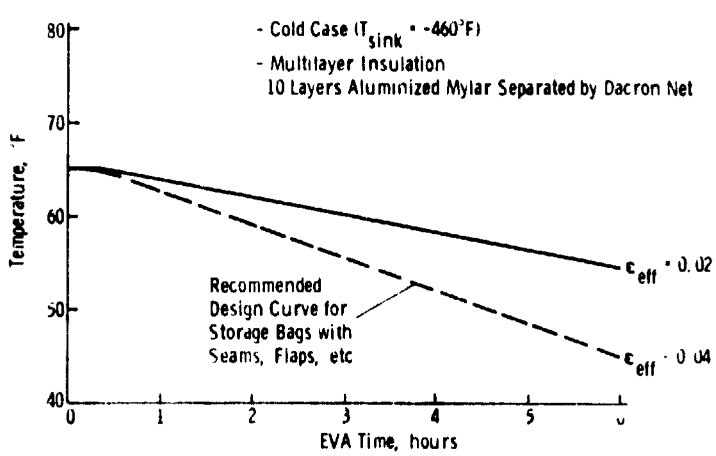


Figure 5-9 Thermal Control - Applicator/Mixer

5.3 FUNCTIONAL MOCKUP

The functional mockup of the self-contained concept, as shown in Figure 5-10, was operated using a simulated catalyst glass tube filled with ferric oxide in suspension with ablator material to visually illustrate mixing action. The mixing test, using the white ablator, showed good internal mixing of the ablator and simulated catalyst with some surface areas on the transparent cyclinder still showing white and red streaking. The mixing was done by hand crank and the paddles rotated for 120 revolutions. The expulsion of the ablator was done by air pressure with the resulting flow rates shown in Figure 5-11. The maximum pressure tested, 30 psi, yielded a flow rate of 21 in.^{3}/min.

The functional mockup was used to mix (with a motor) and dispense actual catalyzed MA 25S. The unit incorporated a teflon wiper on one side of the mixing paddles to increase mixing on the cylinder sides. Due to the mockup-peculiar concept (not contained in recommended design), some mixing is restricted in the forward end. The mixed ablator was expelled through the nozzle into four blocks (size 3x3x1 in.). Data on the cured MA 25S are listed and indicate satisfactory mixing of the ablator and catalyst:

1) Gel time approximately 70 minutes;

2) First block 18-hr cure,

    a) Shore A hardness 35-40,
    b) Bond tension 51 psi;

3) Fourth block 18-hr cure,

    a) Shore A hardness 35-40,
    b) Bond tension 65 psi.

The functional mockup was modified to incorporate the three-part concept by adding a 3-foot feedline to the exit of the applicator/mixer unit and adding a hand flow control applicator unit to the end of the feedline. The unit requires a pressure of 100 psi to deliver 21 in.^{3} per minute. The unit was demonstrated up to a 90-psi expulsion pressure.

The mockup was delivered to NASA-JSC on November 19 and mixing was demonstrated for NASA personnel. The unit was left with NASA for a KC-135 zero-g flight demonstration of ablator application.

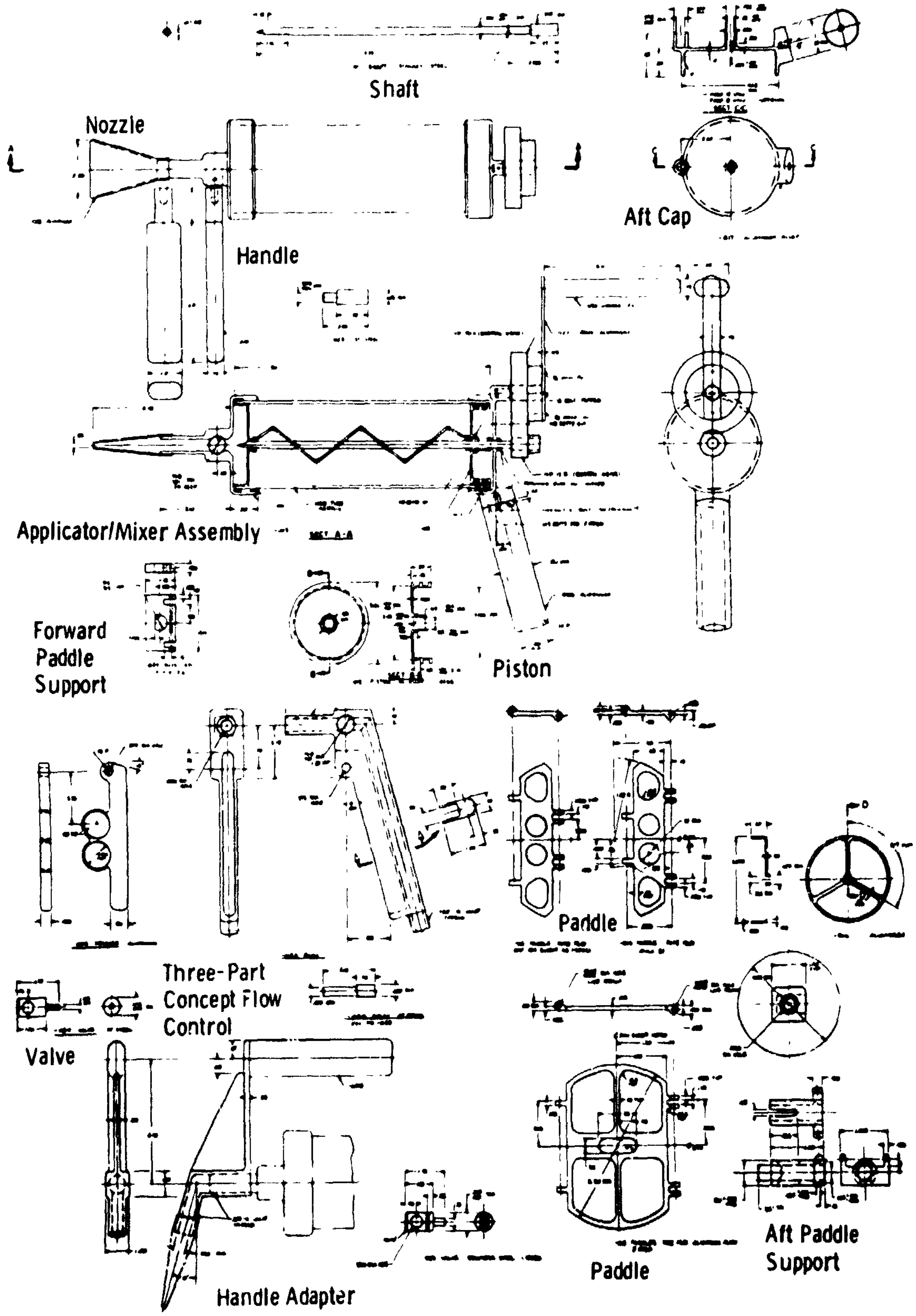


Figure 5-10 Functional Mockup of Applicator/Mixer

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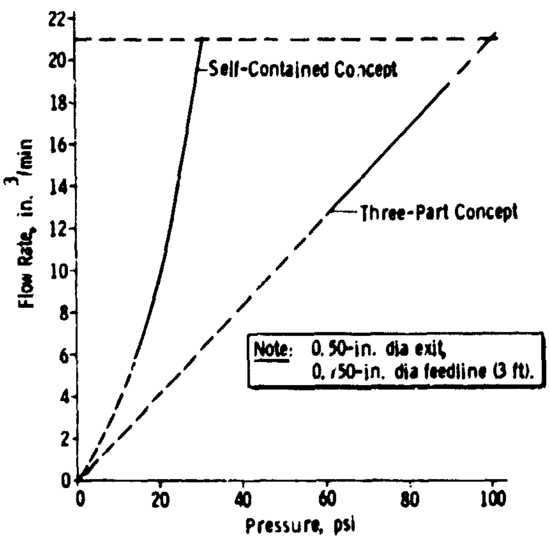


Figure 5-11
Nozzle Exit Flow Rates vs Expulsion Pressure

5.4 STORAGE CONTAINER FOR REPAIR KIT BASELINE DESIGN

The repair kit storage container has a 12-ft^3 volume and measures 22.0x25.0x37.7 inches overall. The configuration for the applicator/mixer self-contained concept is shown in Figure 5-12. The eight units are stored for individual access and return with the left door open. The units are hard-mounted to forward and rear rails. Release of the forward restraint allows the units to be removed one at a time and replaced after individual use. The kit tools and mixing gearmotor/battery assemblies are mounted on the left door (inside) for easy access and replacement. The right-hand door opens the egg-crate restraint for all of the precured ablator blocks packaged and color-coded as to thickness sizes. The blocks are bagged as shown for transfer to the MMU work restraint transport container. The upper compartment is for the coating repair cans (provided by NASA-JSC).

The doors are restrained open during unloading and loading operations but are closed, using the magnetic latch only, during repair operations.

The figure illustrates a typical transfer bag of precured ablator blocks showing teflon divider sheets to allow easy removal of individual blocks. The divider sheets are tacked to the rear of the bag to prevent them from coming out. Each row of block packages in the egg-crate divider are soft-restrained by a Velcro-attached strap to prevent the bags from drifting out. The bags have pull tabs and Velcro strips for restraint within the caddy.

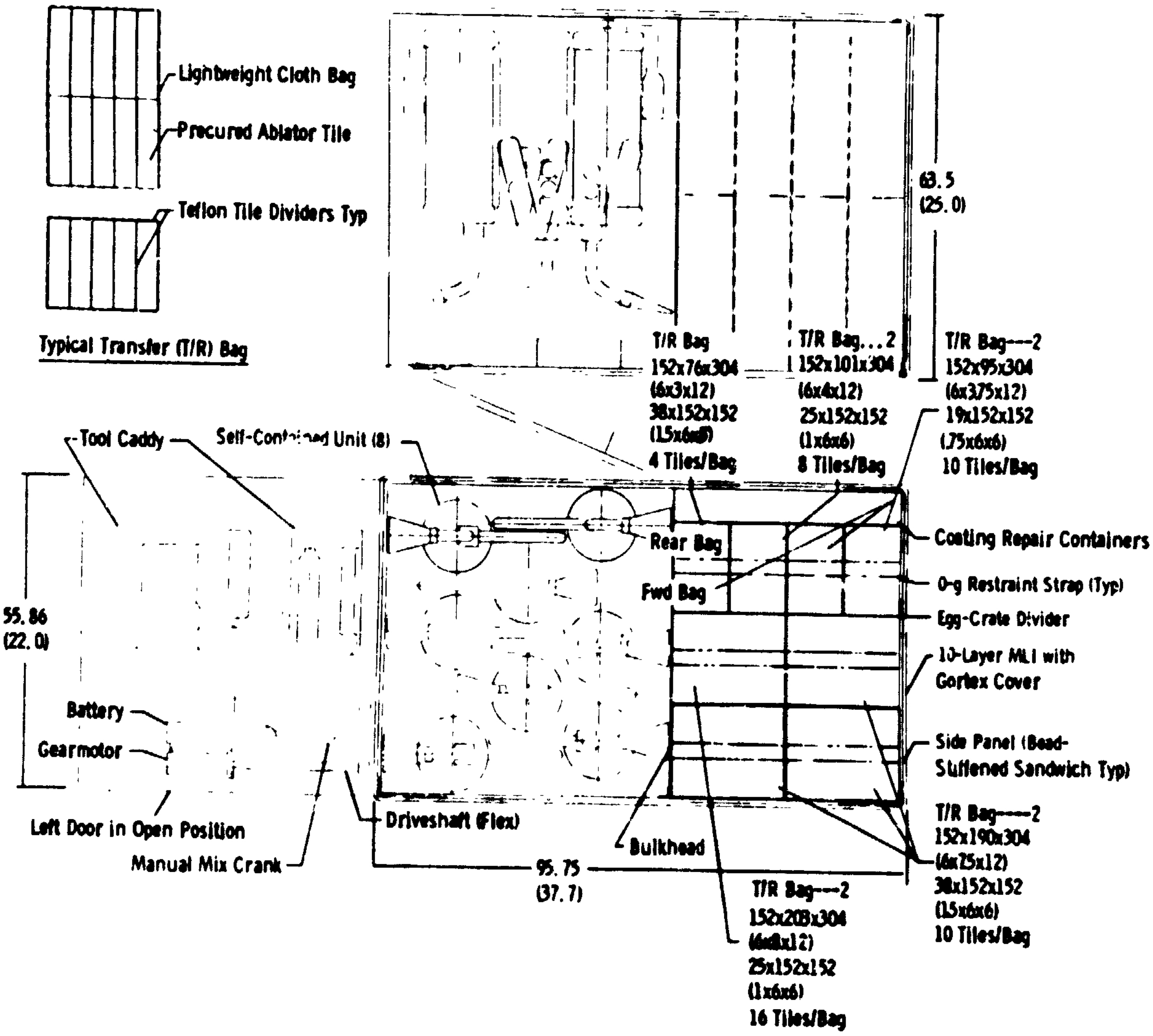


Figure 5-12 Storage Container, Self-Contained Concept

The TPS repair kit container is attached to the ancillary equipment support assembly (AESA) in the orbiter payload by four bolts and is covered with 10-layer MLI with a Goretex cover. The attachment bolts are thermally isolated from the support structure by thermal washers. The box is actively heated by seven strip heaters bonded to the inner aluminum surfaces (one per outer surface plus an additional one on the second door). Thermostats are mounted in the applicator/mixer compartment. Figure 5-13 shows the three-part concept mixing application system storage container. The right-hand compartment is unchanged from the previous storage container of Figure 5-12, but the arrangement of the mixing pots and feedline-hand control applicator assemblies are unique to this concept. There are four mixing pots and feedline applicator assemblies. The latter are mounted to the inside of the left door with the automix gearmotor/battery assemblies and tools as shown.

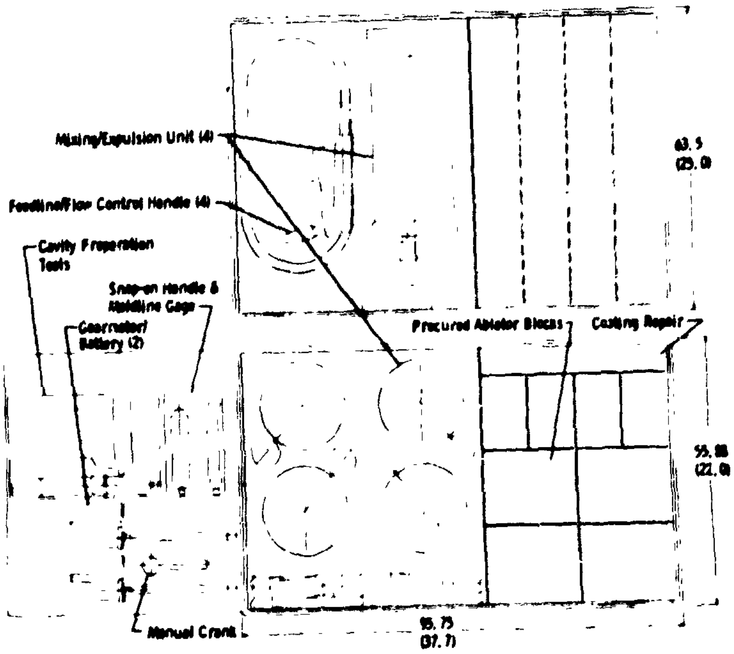


Figure 5-13
Storage Container, Self-Contained Concept

The weight statement for the self-contained concept is shown in Table 5-3 and for the three-part concept in Table 5-4.

Table 5-3
Repair Kit Weight Statement,
Self-Contained Applicator/Mixer

Item	Weight, lb
8 Applicator/Mixer Units (Includes 10% Contingency)	62.9
Cure-in-Place Ablator (in Units)	41.4
Precured Blocks SLA 561	49.2
Coating Repair Cans (Includes 10% Contingency)	20.0
Soft Carrying Bags	2.4
Repair Kit Container	44.3
Gearmotor/Battery Pack (2)	11.0
Tools	5.0
Contingency (10%)	2.0
Gross Weight	238.2

Table 5-4
Repair Kit Weight Statement,
Three-Part Applicator/Mixer

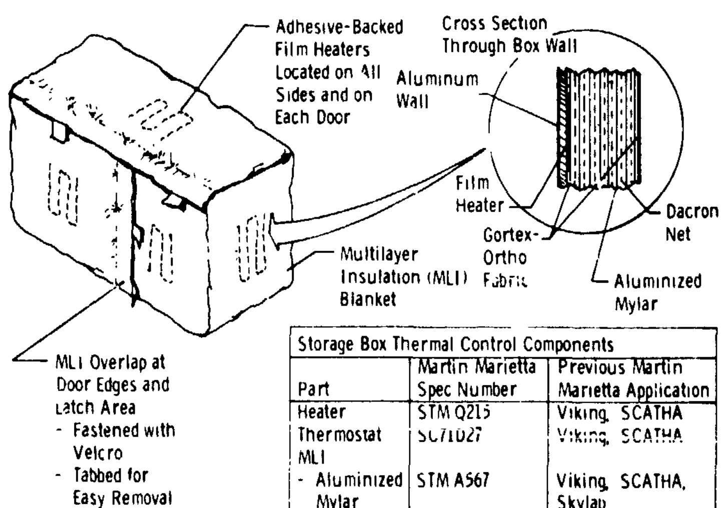
Item	Weight, lb
4 Applicator/Mixer Units (Includes 10% Contingency)	109.7
Cure-in-Place Ablator (In Units)	55.3
Precured Blocks SLA 561	49.2
Coating Repair Cans (Includes 10% Contingency)	20.0
Soft Carrying Bags	2.4
Repair Kit Container	44.3
Gearmotor/Battery Packs (2)	11.0
Tools	5.0
Contingency (10%)	2.0
Gross Weight	298.9

The baseline structure uses a sandwich shell of bead-stiffened outer panel spot-welded to an inner sheet of aluminum alloy. The concept is illustrated in Figure 5-12. This construction leaves the inner surfaces of the box smooth and clear for loading TPS repair items. The panels are riveted to angles at the edges, and there are special hard-restraint rails for the mixing pots or units. The egg-crate divider for the precured ablator block packages is a subassembly.

The doors are piano-hinged on the sides, with both hard latches and magnetic soft latches used for closure during TPS repair. The hard latches are used before and after EVA repair operations.

5.5 STORAGE KIT THERMAL CONTROL

The thermal control function of the storage container is to maintain ablator material temperatures at their optimum working condition. As noted in the previous section, a 63°F storage temperature has been selected as optimum for our MA 25S cure-in-place ablator material. The thermal control system required to maintain this temperature is shown in Figure 5-14. It consists of dually redundant adhesive-backed film heaters mounted on each side and door of the storage container box. They are controlled by dually redundant thermostats also located on each side and door. The box is enclosed in multilayer insulation (MLI) consisting of 10 layers of 1/2-mil aluminized perforated mylar separated by dacron net. The outer and inner layers of the blanket are covered with Gortex-Ortho fabric cloth. This cloth prevents tearing of the mylar, and its low solar absorbtivity (0.18) reduces the temperature when exposed to the solar heat flux. It also allows the use of Velcro fasteners for door insulation overlaps to minimize heat losses at blanket junctions. The blanket minimizes the heat loss in the cold case and lengthens the temperature response time when exposed to the sun.



Storage Box Thermal Control Components		
Part	Martin Marietta Spec Number	Previous Martin Marietta Application
Heater	STM Q215	Viking, SCATHA
Thermostat	SC71D27	Viking, SCATHA
MLI		
- Aluminized Mylar	STM A567	Viking, SCATHA, Skylab
- Dacron Net	STM 985	Viking, SCATHA, Skylab

Figure 5-14 Thermal Control of Storage Container

The heaters require a total power input of 100 watts--75 watts are lost through storage container external surfaces and 25 watts are lost through the container attachment points. The latter loss is an estimate since the mounting interfaces have not yet been established. The interface assumptions used for this estimate are:

1) Orbiter mounting structure temperature = $-215^{o}F$;

2) Total attachment surface area = 5 $in.^2$;

3) 1/2-in. thick attachment area isolator block;

4) Isolator block and washer thermal conductivity = 0.15 Btu ft-h^{o}F;

5) Five 1/2-in. steel bolts with 1/16-in. thermal isolator washers.

The 75-watt loss through the container surfaces was based on an effective MLI blanket emissivity of 0.04. This value has been established from flight measurements of similar MLI configurations on Viking and SCATHA and accounts for the deleterious effects of seams, joints, etc in relatively small insulated box-type applications.

The design "hot condition" involves a long-term exposure to the sun as well as $200^{o}F$ temperatures on the payload bay liner. Although the large heat capacity of the loaded storage container will slow the temperature response to this environment, the desired $63^{o}F$ storage temperature could be exceeded during a long-term exposure. However, the maximum 55-minute solar exposures anticipated during the first Shuttle flights are not expected to significantly perturb this temperature. Once the attachment interfaces have been defined, the "hot" and "cold" design conditions can be thermally analyzed. Results from the "cold" analysis will allow selection of individual heater sizes for each side of the box. The results from the "hot" analysis will provide the maximum allowable time for continuous solar exposure. After this exposure time the orbiter attitude would have to be changed.

5.6 TOOLS

5.6.1 Requirements

The major requirements include:

1) Tools must be provided for surface preparation, spreading, and outer moldline verification;

2) Must be tethered;

3) Must be compatible with EVA-suited crewmember;

4) Have no sharp corners or edges and all corner radii must be 1/4 in.;

5) Require no more than two tools for surface preparation.

5.6.2 Tool Baseline Design

The tools for the baseline concept are shown in Figures 5-15 through 5-18. The backup mixing mode hand crank is shown in Figure 5-15. This is a 4.5-inch radius crank with a ball handle. The unit snaps on the mixing shaft for manual cranking in event of loss of automixing capability. The unit has a Velcro strip as shown for soft restraint.

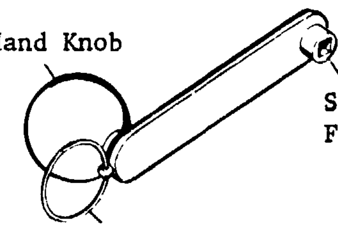


Figure 5-15
Hand Crank Backup Mix Mode

Figure 5-16 shows the prying tool and multiuse trowel used as required for preparing the TPS area for repair, smoothing the repair (if required), and any general use such as aid in setting the precured ablator tiles in place on the cure-in-place adhesive.

Figure 5-17 illustrates an extensible moldline gage for checking the required $\pm$0.25-inch requirement to outer moldline of the existing TPS tiles. The gage shows the limits at a glance.

Trash bags are included as tools for collecting large pieces of tile debris during preparation of the area to be repaired.

Figure 5-18 shows the cavity preparation tool, which is a modification of a diver's prying tool.

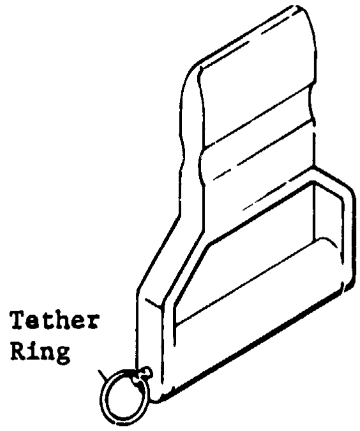


Figure 5-16
Cavity Preparation/Trowel

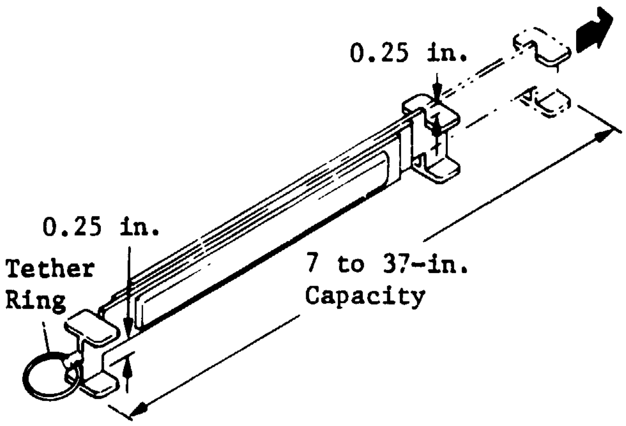


Figure 5-17
Extensible Molding Gage

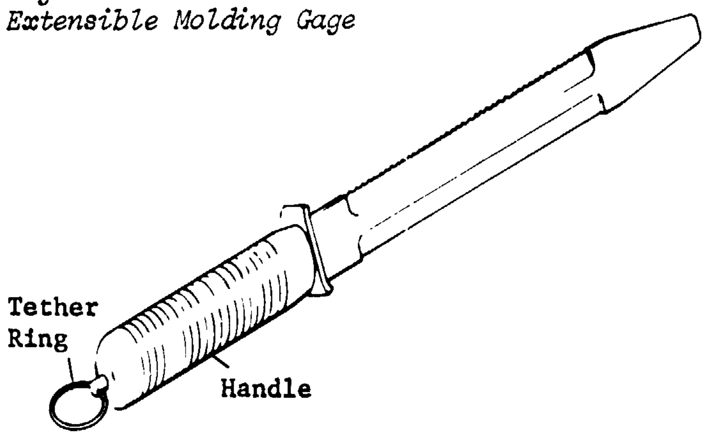


Figure 5-18
Cavity Preparation Tool

6.0 CONCLUSIONS

The conclusions reached in this contract are presented for the various areas of effort:

1) Requirements - All requirements can be satisfied;

2) Materials, cure-in-place,

   a) MA 25S Type III selected,
   b) Compatible with RTV 560 and precured ablators,
   c) 15-minute to 1-hour gel times can be obtained in the *in situ* vacuum chamber.
   d) Use of RTV 511 resin has provided small variance in gel time from 40 to 125°F and exhibits application flexibility; no heater is required in applicator/mixer,
   e) Use of RTV 511 resin has provided higher bond tension,
   f) Acceptable vicosity obtained for mixing and dispensing materials (including vacuum),
   g) Material can be made *in situ* vacuum chamber with essentially no voids,
   h) Plasma arc testing - All candidate Type III materials performed well and RTV 511 resin provided improved thermal performance (less char, lower backface temperature and less swelling),
   i) *In situ* vacuum chamber vital to material evaluation;

3) Materials, precured,

   a) SLA 561 selected,
   b) SLA 561 performed well in plasma arc testing;

4) Flight thermal performance analysis - Both MA 25S Type III and SLA 561 satisfy thermal performance;

5) Crew operations and repair approaches,

   a) Development of work restraint must complement repair kit transfer and site usage,
   b) Applicator/mixer unit design features were optimized for EVA usage,
   c) Three thicknesses of precured ablator are desired,
   d) Crew EVA use requires maximum gel time;

6) Packaging definition,

   a) Applicator/mixer unit, self-contained concept - 162.5 in.^{3} usable volume is near optimum for repair task(s) (size can be handled by EVA crewman and units are compatible with container packaging constraints),
   b) Applicator/mixer unit, three-part concept - 390 in.^{3} usable volume is a size that can be packaged (4 per kit) and handled by EVA crewman,
   c) Redundant mixing modes (hand crank and motor) are desirable and provided for,

d) Several soft bag/modules containing mix of applicator/ mixer units, precured ablator, and coating spray cans should be packed within the TPS repair kit container,
e) Tools will use Shuttle contingency tool caddy approach;

7) Functional mockup demonstration,

a) Mixing and expulsion systems are viable,
b) Flow rates are controllable by one hand and are variable and shutoff is positive,
c) Side handle on self-contained unit creates an optional concept with good EVA crew visibility to the applicator nozzle,
d) Three-part concept utilizes a small one-hand control/ nozzle applicator,
e) Motorized mixing times of approximately 3 minutes are achieved.